Project no. 265863

ACCESS

Arctic Climate Change, Economy and Society

Instrument: Collaborative Project
Thematic Priority: Ocean.2010-1 “Quantification of climate change impacts on economic sectors in the Arctic”

D4.41 – Oil spill response capabilities and technologies in ice-free and ice-covered water

Due date of deliverable: **30/01/2012**
Actual submission date: 30/07/2012
Used Person/months: ...

Start date of project: **March 1st, 2011**

Duration: **48 months**

Organisation name of lead contractor for this deliverable: **SAMS**

Project co-funded by the European Commission within the Seventh Framework Programme (2007-2013)		
Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

ACCESS
Arctic Climate Change
Economy and Society

SEVENTH FRAMEWORK
PROGRAMME

Task 4.4.1 Assessment and recommendations regarding oil spill response capabilities and technologies in ice-covered waters

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ACCESS is a 4 year European program (2011-2015) supported within the Oceans of Tomorrow call of the European Commission Seventh Framework Programme. For further information about ACCESS please visit our website at www.access-eu-org

Forward

It is predicted that commercial investment in the Arctic could reach $100bn or more in the coming decade, with oil and gas, mining and the shipping industries being the biggest drivers. This is understandable as recent estimates suggest 30% of the world's undiscovered gas and 13% of the world's undiscovered oil are to be found in the shallow, seasonally ice-covered, coastal regions. In addition to the possible hydrocarbon reserves the continuing reduction of Arctic sea ice pack in summer has significantly extended the navigation season, reigniting the debate regarding the viability of Arctic sea routes, a saving in distance of up to 40% over traditional routes. This 'industrialisation of the Arctic' seems to be driven by a combination of climate change and the ever-increasing demand, and price, for oil and minerals.

The remoteness, lack of infrastructure and extreme conditions of the Arctic will obviously create challenges far any oil spill response, and because of this oil spill contingency and response strategies vary considerably between open water and areas with a sea ice cover. Furthermore the temporal and spatial variability of Arctic meteorology and sea ice means that we need strategies that are tuned to the appropriate ice and weather conditions.

The aim of all oil spill response techniques is to reduce the amount of contact, or exposure, to organisms that might be affected by contact with the oil, or concentration of components from the oil. The degree of effectiveness of the response technique is the degree to which the damage that could have been caused by the oil is reduced. This report provides an assessment of the present oil spill response capabilities and technologies in ice-covered waters and brings together knowledge that has been amassed over many decades; including the significant review papers that have been prepared as well as more recent laboratory tests, field programmes and modelling work. The main areas covered by the review include:

(1) Oil-ice interaction, weathering and modelling,
(2) Oil detection and monitoring,
(3) Oil Spill Response Techniques,
(4) Scenarios for oil spill response in ice-covered waters.

We acknowledge that there are limitations within our review, for example it was not possible to provide comprehensive descriptions of the many and varied coastal and marine habitats and ecosystems present in the Arctic. This report is one of many deliverables that will enable the ACCESS (Arctic Climate Change, Economy and Society) programme to produce an across-the-board understanding of the socio-economic impacts associated with Arctic change, together with an understanding these change will have on European policy, markets, economies, and Arctic governance.

Executive Summary

The impact and consequences of an oil spill in the Arctic marine environment will be immense. Locally it will impact the ecosystem and the livelihoods of the local communities that depend on them for a living. Globally, the impact will be much more substantial. How will citizens, governments, NGOs, industry and policy makers react to an Arctic spill? How will it influence future economic and development activities across the Arctic? How will it effect the reputation of the companies involved? And what will the socio-economic impact of an Arctic oil spill be for Europe?

We cannot presently answer these questions, but if robust and efficient countermeasures are in place, as well as a clear risk-management structure, then the impact of a spill will be minimised. Good governance, high international standards and practices, and comprehensive but responsive regulatory regimes are in everyone's interest. By applying a Rumsfeldian type of classification system to our present knowledge of oil ice spills in ice-covered seas we have:

Known-knowns: Over 40 years of research in the field of oil spills in ice-covered seas have provided good baseline knowledge along with applied solutions to spills in the Arctic marine environment.

Known-unknowns: Numerous reports (including this one) by academia, governmental organisations, and industry have highlighted the successes as well as the failings associated with oil spill contingency and response strategies for the ice-covered seas. These holes in our knowledge form a critical deficit affecting all aspects of a response to an Arctic marine oil spill. They must be urgently addressed. See the following Recommendations section.

Unknown-unknowns: Due to the complexity of the Arctic environment, the complexity of the processes that govern the weathering and trajectory of oil spill in this system, the difficulties of conducting an oil spill response operation in the region, and (thankfully) that a major spill has not occurred in the Arctic there will always be unknown-unknowns. We hope these are small in number.

Given the harsh environmental conditions within the Arctic marine environment the safe and efficient extraction of these resources poses many challenges. One of these challenges is ensuring common standards, transparency, and best practice applies across the Arctic marine environment. This is in everyone's interest and will provide a framework for a comprehensive oil spill response strategy that covers the range of oil properties, logistic capabilities and environmental conditions experienced in the Arctic.

Recommendations

It has long been recognised that the Arctic marine environment is one of the most challenging areas in the world to operate in. Even with this knowledge development in the north has progressed substantially since the 1970s, both on land as well as in some of the shallower regions of the Arctic marine environment. Recently there has been renewed interest in the northern Polar Regions, and the pace of activity in the marine environment has increased substantially. It is important to remember that all this activity has been authorised by the relevant Arctic States, and is conducted within their jurisdiction.

As a result of this economic and industrial history there is a wealth of technical expertise, experience and know-how in operating under Arctic conditions. This knowledge also extends to oil spills in ice-covered seas. Nevertheless there are gaps in our understanding that need to be addressed urgently so that these gaps can be bridged and solutions found. In some cases however the challenges may be greater that the expertise in one country, sector or scientific discipline and therefore the combined efforts of a wide variety of international experts will need to brought to bear on these challenges.

In producing this review there seems to be a polarised view regarding the extent of the gaps in our knowledge. Some organisations feel that these gaps are so serious that there should be a moratorium on oil exploration/exploitation in ice-covered water, whilst others feel that these knowledge gaps have already been solved and adequate processes are in place. Because of these deeply divided opinions there is a level of responsibility that lies with the Arctic Ocean States themselves, Norway, Greenland (Denmark), Russia, United States and Canada to ensure that the industry always operates at the highest environmental and technical standards. At present each country has independently developed their own legal regimes under which industry operates within their EEZ. Under the guidance of the Arctic Council for example, and in collaboration with regulators, industry, local communities, NGOs and other valued stakeholders, these States could set pan-Arctic legally-binding rules and regulation for oil and gas operations in the marine environment.

These regulations should not inhibit the right of a State to exploit their resources, but deliver a strong regulatory framework that will provide clarity for industry and ensure that best available practices are followed right across the sector. By doing so the socio-economic impact of an increased industrialisation of the Arctic i.e. resource extraction, shipping, tourism and fisheries, is likely to more sustainable in the short to medium term.

Should an accident occur in Arctic waters it is clear that the difficulty of an Arctic clean-up combined with the environmental and political consequences means that it will be expensive, financially, environmentally, and reputationally. Benjamin Franklin's quote "*An ounce of prevention is better than a pound of cure*" still rings true today and therefore robust countermeasures need to be in place to ensure as little oil as possible is released to the ocean surface or the underside of the sea ice. No one can guarantee an accident cannot happen, but if a State ensures that robust risk management frameworks and best practice processes are in place the likelihood of an accident will be reduced.

Knowledge gaps in our oil spill response capabilities

It is well known that there are significant differences between oil spill response capabilities in open water to that in an ice-covered sea. In fact our review clearly shows that significant differences also exist for spills occurring within different types of sea ice and seasons; for example the response to a spill within fast ice will be different to drifting ice, new ice to old ice, and level ice to deformed ice.

There is a lot of misapprehension surrounding oil spill response capabilities and technologies in ice-covered waters. It is possible that many of these misunderstandings are due to the lack of information that is publicly available in peer-reviewed journals. We can not be complacent however, and practical steps need to be taken to ensure that the systems and procedures we have in place are robust enough to deal with all environmental conditions, especially worst case scenarios. In order to fully comprehend our level of understanding and readiness to deal with an Arctic oil spill field exercises that encompasses a broad spectrum of sea ice, ocean and meteorological conditions are desperately needed. Whilst a handful of field-based test spills have occurred in the past a further series of focused field trials are needed (under different conditions) if oil spill response capabilities and technologies are to be evaluated. There is urgency to this as exploration and shipping in the Arctic is well advanced, we just need to look at the Arctic seas around Russia, Greenland, the United States and Canada. Our recommendations for further research include:

Oil spill modelling

The accuracy of an open-ocean oil spill model can be validated by the analysing data from various spills that have occurred under different weather and oceanic conditions. For example modelled oil trajectories can be validated against daily spread of oil as detected by satellite or airborne sensors. There are no *in situ* data for the validation of oil trajectory and fate models for the ice covered seas.

To address this omission an *in situ* oil spill and measurement campaign is needed to gather an ‘open’ dataset that oil spill modelling teams can use validate their model simulations. This publicly available, benchmark dataset would be used to identify discrepancies between model output and observations, enable parameters within a model to be tuned, and allow for new algorithms and parameterisations to be developed as and when needed.

Without validation it is easy to fall into the trap of trusting the output of a model without question, and the age old cliché that a model is only as good as the parameterisations and the input data provided remains true. A clear understanding of the limitations of a model is essential and without a benchmark dataset the modelling community cannot judge the accuracy of their models.

Detection

Detection of oil spills by sensors that can cover large areas quickly and accurately are preferable. For open water spills this is achievable with satellite or airborne sensors, and results suggest that these techniques are expected to work for oil spill detection in very open drift ice, up to 3/10ths concentration. In heavier ice concentrations the sensor performance and detection capabilities are less robust.

As the concentration of ice increases the likelihood of oil being located under (or within) a sea ice cover also increases. The detection of oil under sea ice is a difficult task, but investment and research in this field have delivered a number of sensor technologies that have the potential to detect and map oil under or within sea ice. However, our review suggests none are truly operational at present. The advantages and limitations of the most promising technologies to detect oil under different sea ice, oceanographic and meteorological conditions need to be fully established.

The most appropriate way of doing this is through dedicated oil-spill field trials that are performed under various environmental conditions. The results of these trials should be published in peer-reviewed journals. Any limitations need to be openly acknowledged and where needed suitable alternatives found. Once suitable technologies have been identified it is essential that investment continue to ensure operators are au fait with the routine deployment of these instruments under different environmental conditions, and proficient with the accurate and timely interpretation of resultant data.

Weathering:

The fate and behaviour of oil spills in the marine environment is an extremely complex subject. It is fundamentally important to understand both how the weathering processes evolve with respect to the environmental conditions encountered, and how these processes interact both temporally and spatially to alter the properties and behaviour of oil. This is extremely difficult to perform in the Arctic, as it requires the long-term monitoring of specific spills of different oil types in the marine environment. Tank experiments are extremely valuable and can give insights into some of the natural weathering processes, but they cannot replicate the complexity of the marine environment.

Other areas that need further investigation include biodegradation processes in Arctic waters, quantifying the relative importance of the different natural weathering processes at different times of the sea ice growth and decay process, and the parameterisation of the vertical migration of oil through sea ice during the summer months.

Oil spill response techniques

There have been many research programmes into methods of oil spill response in ice-covered waters including containment and mechanical recovery, burning, bioremediation, and enhanced dispersion. Some oil spill response methods that would be feasible or effective in open water condition are of limited value in the ice infested waters. Furthermore the effectiveness of in-ice response methods varies depending on the ice, ocean and meteorological conditions. Essentially each season presents different advantages and drawbacks for spill response. A review of the literature suggests significant long-term investment in this field has been made and there are a number of possible techniques available. However it was difficult to establish exactly what range of environmental conditions each system could operate in. There needs to be a focus on establishing the efficiency and effectiveness of each system under a range of ice conditions and weather conditions.

Many of the human-invention techniques such as burning and dispersants remove oil from the ocean surface, however their impact on the Arctic ecosystem is unknown. Studies need to be performed to quantify their impact of the marine environment and how this impact varies both temporally and spatially.

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1. Introduction

by

Jeremy Wilkinson, Scottish Association for Marine Science

The Arctic Ocean holds some of the world's largest remaining oil and gas reserves. Almost all of these reserves are found in the biologically productive, and seasonally ice-covered, shelf sea regions of the Arctic states. The unprecedented retreat of Arctic sea ice, combined with the increasing value and scarcity of oil and gas finds suggest that the expansion of shipping and oil/gas exploration into these areas is inevitable. Any increase in human activity in the ice-covered waters will magnify the potential for an oil spill; whether it is from a shipping accident, subsurface pipeline leaks, or a subsurface blowout. An oil spill will be devastating, and potentially unrecoverable, to a fragile Arctic marine environment that is already-stressed by climate change. Within this chapter we provide an overview of the lifecycle of sea ice, the climate induced changes that have occurred to Arctic sea ice, and how these changes are influencing shipping traffic and hydrocarbon exploration and exploitation.

1.1 Sea ice

When heat is lost from the ocean surface to the atmosphere the top-most layer cools, becomes denser, and sinks, which in turn causes an upwelling of warmer water. As more heat is lost to the atmosphere thermal convection will continue to bring deeper, warmer water to the surface. This will continue until the freezing point of the water column, determined by its salinity, is reached. Once the surface of the ocean is cooled to freezing any additional heat loss produces the formation of small crystals known as **frazil ice**. Frazil first appears as an oily sheen on the surface of the ocean, which is referred to as **grease ice**. The smooth appearance results from the dampening of short gravity and capillary waves (the high frequency end of the wave spectra) on the water surface. Frazil inhibits breaking waves, decreasing the turbulence in the upper ocean. If both the wave and wind effects are reduced the agitation of the frazil ceases and the surface layer of frazil crystals can begin to consolidate. As the upper frazil layers have a greater propensity for heat loss, due to exposure to the cold atmosphere, they preferentially fuse together to form **nilas.** Nilas is extremely plastic and can easily bend with the waves. Further thickening will continue as an unidirectional process by which seawater freezes directly to the underside as heat is conducted through the ice. This is known as congelation growth. This is the start of sea ice forming a continuous, thick sheet.

However if the wind reduces but the swell persists frazil will continue to be agitated. Under the motion of the waves this newly formed crust of ice does not form nilas, but is broken into small rounded shaped pieces normally a few tens of centimetres in diameter, known as **pancake ice**. The diameter of primary pancake ice depends on the high-frequency part of the wave spectrum.

The covering of the sea surface with pancakes and frazil further dampens any penetrating high frequency waves, allowing the low frequency waves to become more prominent. As the lower frequency waves become more dominant less flexure is exerted on individual pancakes and their horizontal extent increases. This is generally accomplished by the freezing together of several smaller pancakes, although frazil accumulation around the edges will also enlarge the pancakes. Once the incoming wave energy has decayed sufficiently pancakes will freeze together, with the frazil acting as the adhesive, to form an extensive sheet. From then on, further thickening will occur as per the congelation growth for nilas sheets described above.

If at any stage the penetrating wave energy increases sufficiently the newly formed ice sheet will be broken up into individual **floes**, the size of which will be determined by the incoming wave spectra. Between the floes will be a combination of broken ice of varying sizes, smaller floe pieces known as **brash** ice, and newly formed pancake and frazil ice. When the wave energy decreases suitably this mix of different ice types and sizes will freeze together with the floes to form a new ice sheet

Once a continuous ice sheet is formed it is collectively know as **first year ice** (FY). Generally ice formed at the start of the winter is 1-2 m thick by the beginning of the following melt season and the surface smooth in appearance. FY ice that survives the summer melt then becomes known as **Multiyear ice** (MY). MY year ice can be many years old and is generally thick and heavily deformed. With respect to the morphology of the underside ice, FY ice is regarded as smooth whereas MY ice is quite rugged as a result of the differential melt/growth rates throughout the seasons (Wadhams, 1985).

Once formed most sea ice drifts with the wind, although wave action, currents and tides also play their role in the dynamics of ice (Leppäranta, 2005). Ice that is frozen to the shore and not able to drift is known as land-fast ice. Drifting ice can be pushed together by converging winds, generating ice pressure, to form **ridges** or torn apart to form **leads** by diverging winds. These processes affecting the morphology of sea ice continue throughout its lifetime, and therefore morphology of sea ice is shaped by the conditions under which it formed as well the thermodynamic (growth and melt) and dynamic (ridges and lead formation) processes that occur during its lifetime. As a result sea ice can show great variability in its structure.

In summer the snow and ice melts and **melt ponding** is common. Rridges and hummocks become smaller and more rounded due to the melting process. Thinner ice types generally fully melt during the summer months. A schematic representation of the annual sea ice cycle can be seen in figure 1.1.

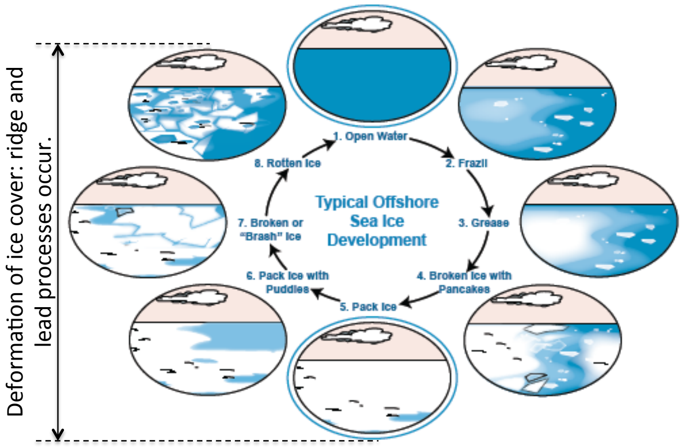


Figure 1.1 Typical sea ice freeze-up, break-up and melt cycle for first year ice. Not shown is the formation of multiyear ice due to rotten and broken ice surviving the summer melt season (Adapted from PEW, 2010).

Other sea ice nomenclature

There are other important classifications to consider that do not relate to the life-cycle of sea ice. These include:

Fast ice (floating and grounded): Fast ice is usually a seasonal sea ice cover that is in contact with the shore, but is immobilised due to the geometry of the coastline or by anchoring points such as small islands or grounded sea ice ridges and icebergs. Fast ice is not mobile therefore when formed in situ is usually in an undeformed state, although there are irregular undulations on the bottom of the ice. These are due to localised changes in the thermodynamic growth rate brought about by spatial variations in snow loading (Wadhams and Martin, 1990). Snow acts as an insulator, reducing the heat exchange between the atmosphere and ice-ocean interface, thus reducing the thermodynamic growth in regions with a thicker snow cover. These natural undulations in the under-ice topography can provide effective catchments to contain any spilled oil (Barnes et al., 1979; Kovacs et al., 1981). Most fast ice melts each summer, however in some regions, like the north of Greenland, fast ice can stay in place for many years. This thick fast ice, with it undulating surface is known by its Inuit name sikussak (Koch, 1945).

Drifting pack. The majority of sea ice within the Arctic is mobile, i.e. it moves under the influence of wind, currents etc. Drifting pack can be further divided down into first year ice (FYI) and multiyear ice (MYI). It is speculated that MYI will have a larger holding capacity for oil than FYI due to its deformed nature, although this has not been confirmed yet. MYI is generally located north of Greenland and Ellesmere Island (Canada) as well as over the deep basins. It is also found in varying quantities in the exit routes for ice leaving the Arctic Ocean i.e. Fram Strait or the Nares Strait/Canadian archipelago system.

Flaw lead or shear zone: The flaw lead or shear zone system is the demarcation zone between the fast ice and the drifting pack. Because the drifting pack is influenced by a number of competing forces the ice cover within the flaw lead or shear zone is continuously developing. For example when the pack moves away from the fast ice a lead system (open water) develops; on the other hand when the drifting pack moves towards the fast ice then deformation of the ice cover occurs, usually in the form of ridge building events. These ridges, consisting of ice blocks and rubble, may become grounded and thus provide additional anchoring points for the land-based fast ice, extending the fast ice zone and/or making it more stable. The underside topography of flaw lead–shear zone systems is unknown and therefore its potential oil holding capacity and how an oil spill will flow under this ice type is also unknown.

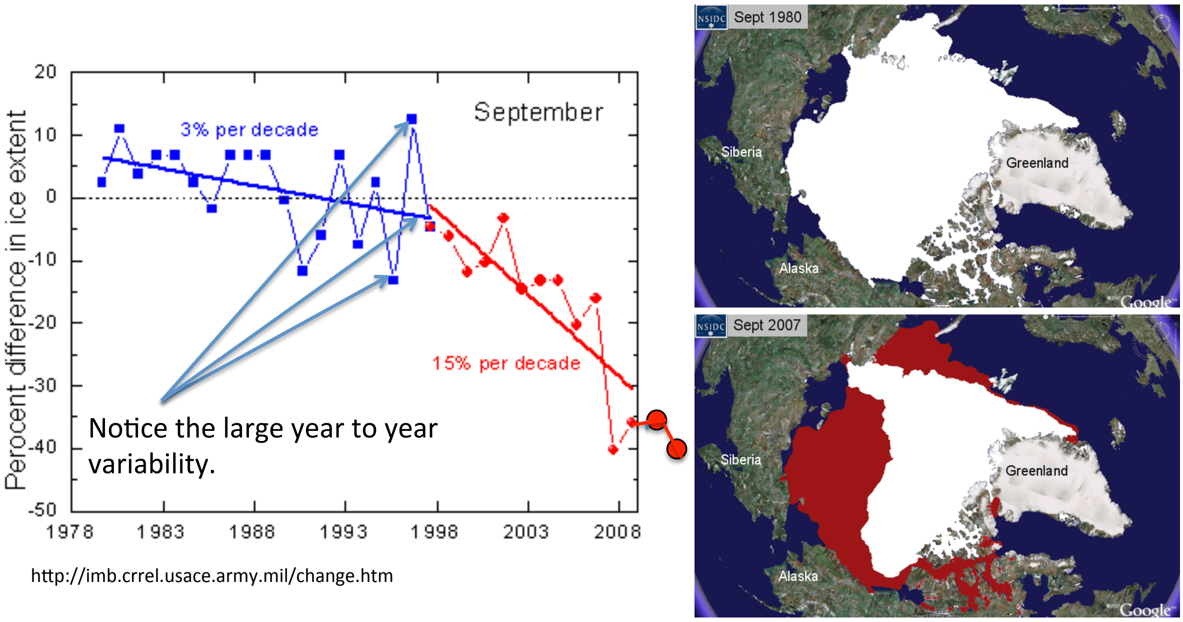
Marginal ice zone*:* The marginal ice zone (MIZ) is not an ice type but the outer region of the ice pack. This region is open to the ocean and as a result it has properties quite different to those mentioned above, and thus deserves a mention. Wave and wind induced break-up leaves the ice as a mixture of broken up floes and smaller floes pieces known as brash. New ice such as frazil and pancake ice are also found within this zone in winter. The ice types within the MIZ are extremely mobile and because of this the amount of open water surrounding the floes is constantly varying.

Icebergs: Icebergs originate from glaciers and thus are of non-maritime origin. Most icebergs originate in regions south of the Arctic Ocean i.e. the Greenland ice cap but other calving areas include the glaciers of Spitsbergen, Franz Josef Land and Novaya Zemlya. As a general rule they are rarely encountered within the Arctic Ocean. In some ways their rarity makes them more dangerous to shipping and fixed assets. Icebergs are more common in the Baffin Bay and the Labrador Sea regions.

Ice Islands: Whilst icebergs are rare in the Arctic Ocean, another form of thick ice, in dimensions often exceeding those of Arctic icebergs, is the ice island. These are areas of ancient, land-fast ice of a draft of about 50 metres and several kilometres in extent, that have broken off from the coastal fringes of Ellesmere Island and other Canadian Archipelago islands. In the past these were more common, providing suitable platforms for long-term scientific stations (e.g. T-3). However, climate change and the subsequent reduction in the size of their sources has reduced their occurrence, but they still remain a potential threat for oil/gas activities in the Beaufort and Chukchi Seas, as well as Baffin Bay and Davis Strait areas.

1.2. Climate change and sea ice

The Arctic is rapidly changing, possibly faster than at any other time during the Earth's history. Recent measurements have clearly shown that the Arctic has warmed faster than any other region of the world (IPCC, 2007). This warming has been accompanied by changes in all aspects of sea ice function; for example we have seen a decrease in sea ice extent of about 15% (Francis et al., 2005), changes in ice type (Wilkinson et al., 2009), a reduction in perennial (multiyear) ice (Kwok, 2007), variations in ice dynamics (Gascard et al., 2008) and a decline by some 40% in the thickness of sea ice (Rothrock et al., 1999) with an associated reduction of 73% in the frequency of deep ridges (Wadhams and Davis, 2001). See figures 1.2 and 1.3 for example of sea ice retreat and loss of multiyear ice within the Arctic Ocean. These changes in sea ice have also been accompanied by changes in oceanic and atmospheric circulation and properties (e.g. Zang et al., 1998), and fresh water fluxes (Dickson et al, 2008).



Notice the large year to year variability.

http://imb.crrel.usace.army.mil/change.htm

Figure 1.2 Satellite-derived estimates of the minimum ice extent during the month of September. Results suggest a reduction of sea ice extent between 1978 and 1998 of 3% per decade, accelerating to 15% per decade from 1998 to 2008. Figure courtesy CRREL

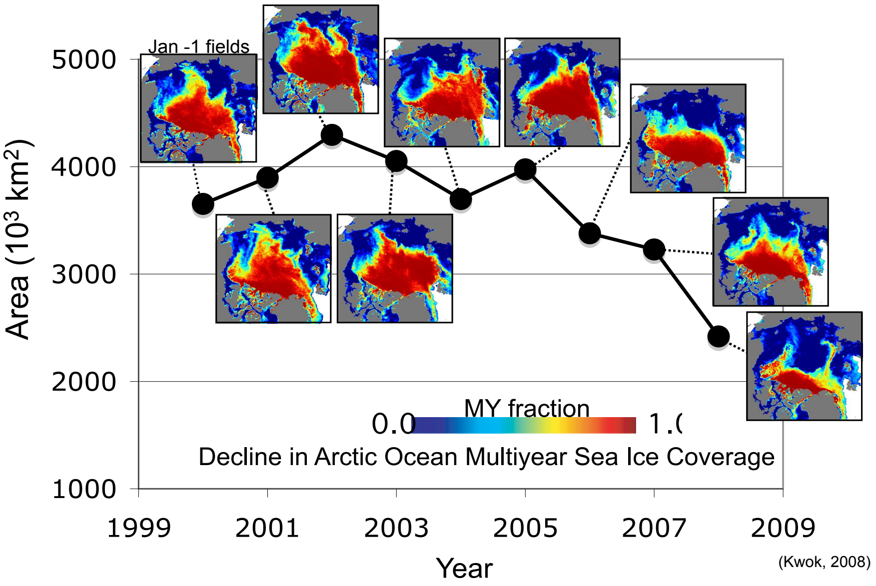


Figure 1.3. Satellite derived of multi year fraction of ice within the Arctic revealing a significant reduction in the amount of Multiyear ice in the Arctic. Arctic sea ice has now changed from a multiyear dominant ice cover to a first year dominant ice cover (from Kwok, 2008).

What is particularly worrying is that the summer sea ice is melting much faster than any climate models has predicted. In fact the observed ice extent deviates well below all model predictions (Fig 1.4). One of the manifestations of these changes is the alteration to the timing and length of the Arctic sea ice melt season i.e. the ice is melting earlier and freezing later (Laxon et al., 2003). Furthermore accelerated change is predicted including a temperature rise of more than 4°C over the next 50 years, particularly over the continental shelves (IPCC 2007) and the disappearance of summer sea ice by 2040 (Holland et al., 2006) or earlier. The socio-economic, environmental, and geopolitical consequences of such a dramatic reduction in the summer sea ice (extent and thickness) are considerable.

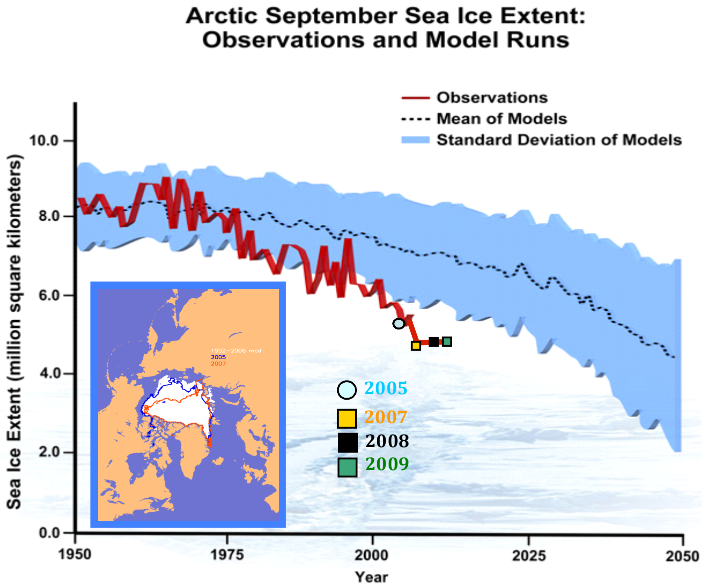


Fig 1.4. Comparison of Arctic sea ice extent between IPCC models (blue) and observations (red). (adapted from Stroeve et al., 2007). Insert: Arctic map showing in white the median ice extent(1992-2006), the blue line is the: 2005 minimum ice extent, and red line is the new 2007minimum.

1.3. *Arctic change and Navigation*

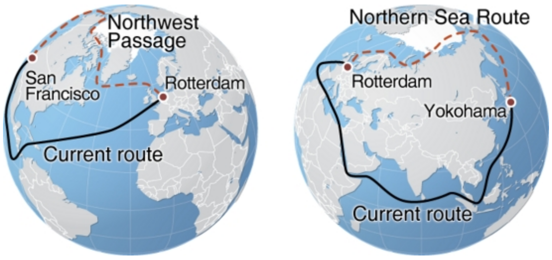


Fig 1.5. The Northern Sea Route and the Northwest Passage compared with currently used shipping routes, Panama and Suez Canals. Based on a figure from Aftenposten, Norway.

The continuing reduction of Arctic sea ice pack in summer has extended the Arctic navigation season, and by doing so has reignited the debate regarding the viability of the North-west Passage (via Canada) and Northern Sea Route (via Russia) for commercial traffic. The shipping of goods from Asia or western North America to northern Europe has traditionally relied on the Panama or Suez Canal (figure 1.5). Shipping via the Arctic Ocean is commercially attractive as it represents a saving in distance (hence cost) of up to 40 per cent, but until now sea ice conditions have inhibited its use. In August 2008, for the first time in recorded history, both the Northwest Passage and Northern Sea Route were open (navigable, with caution) simultaneously. Furthermore in September 2009 two German cargo ships, belonging to Beluga Shipping GmbH, successfully navigated the Northern Sea Route (knocking 4000 nautical miles off the usual 11000-mile journey via the Suez Canal), becoming the first western merchant ships to perform this feat (Reuters, 2009). Cargo ships continue to ply the Northern sea route and in the summer of 2011 both the Northern Sea Route and Northwest Passage were again ”open” simultaneously.. If predictions are correct and the navigation season in the Arctic extends (figure 1.6) then these routes become extremely attractive. In addition to commercial traffic (cargo and tanker) there will also be greater access to Arctic marine resources such as fishing and oil as well as an increase in tourist vessels. The NSR navigation season in 2011 was the longest on record, at 5½ months, with ships transiting from June through to mid-November. However the total tonnage transported was still only one sixth of that achieved under the management of the Soviet Union in the 1980's.

In fact the predicted increase in maritime activity in the Arctic may not only be driven by climate change, but by increasing oil and mineral prices, and tourism (AMSA, 2009). For example, the Russian Arctic holds enormous natural resources which will be increasingly exported by sea. In June 2008 year-round oil shipment from the new Varandey oil terminal (Pechora Sea) began, and by September 2009 it had shipped 7.19 million tonnes (Port News, 2009). Varandey has a capacity of up to 12 million tonnes per year and transports oil, only by tanker, to both European and North American markets (Hurst, 2008).

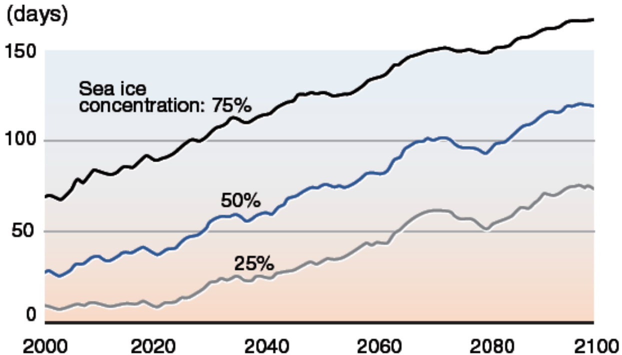


Fig 1.6. Projected increase (days) of the navigation season through the Northern Sea Route (via Russia) as an average of 5 model projections (ACIA, 2004). Note: Arctic sea ice is retreating much faster than model predictions (fig.1) and therefore the above figure should be regarded as the minimum extension of ice free days.

At present the Baltic is the world’s most heavily trafficked sea-route with a seasonal ice cover. These shipping lanes support a large number of ships, each carrying large quantities of their own fuel and oil. However more oil tankers are now plying this route as Russia is increasing its oil export from the St. Petersburg terminal. During winter tankers must pass through the Baltic sea ice**.**

Increased shipping in ice-covered waters will elevate the likelihood of an accident and subsequent oil spill. Particularly because of the lack of experience in large-tonnage tanker navigation under Arctic conditions, unknown bathymetry and the insufficient potential of emergency services (UNEP, 2004). The Exxon Valdez is a poignant example of this (Barinaga, 1989).

1.4. Arctic change and oil exploration

As much as a quarter of the world's undiscovered but exploitable oil and gas reserves may lie in the region north of the Arctic Circle (ACIA, 2004). Recent estimates by the United States Geological Survey (USGS) has revised these figures to 30% of the world's undiscovered gas and 13% of the world's undiscovered oil (Gautier et al., 2009); mostly in Russia, Canada, USA (Alaska), Greenland (Denmark) and Norway (Figure 1.7). The USGS report goes on to state that about 84% of these estimated resources are expected to lie in the coastal offshore regions (shelf seas < 500 m depth).

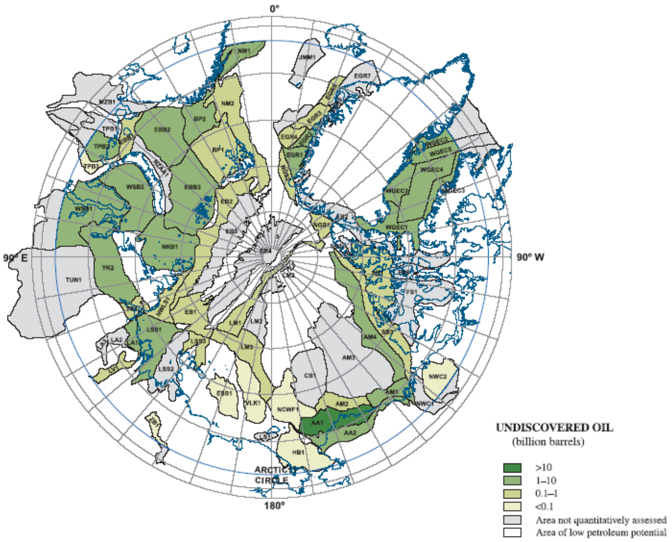


Fig 1.7. Estimates of undiscovered oil and gas north of the Arctic Circle as performed by the Circum-Arctic Resource Appraisal (CARA) group. Notice that most oil (shaded green) lie in the shallow continental shelf seas which are experiencing the largest melt of sea ice. Figure from Gautier, et al., 2009

If this assessment proves correct then most Arctic oil lies in regions with a seasonal sea ice cover. Oil exploration and extraction is governed by economics; in the simplest terms the cost of extraction versus the price of oil. The pressure to exploit Arctic reserves is growing, driven by a myriad of factors:

- high monetary value of the product,
- increasing demand for the product particularly from the newly industrial economies such as China and India,
- unstable political state in some oil producing countries,
- piracy on shipping lanes between traditional oil-producing countries and their markets,
- energy security, e.g. Arctic nations can reduce their dependence on foreign oil through local extraction,
- limited exploration opportunities in other regions and,
- depletion of world reserves in accessible regions[1].

When one combines the above mentioned factors with the unprecedented access to these resources because of the exceptional retreat of the sea ice in summer, Arctic oil becomes very attractive to governments and oil companies. The recent billion-dollar oil and gas lease sales in the Beaufort Sea and the region off west Greenland suggests this is indeed

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[1] Whilst hotly debated, there seems to an agreement between oil experts that we have passed or are very near global peak production (EWG, 2007). After peak oil, the global availability of oil will decline year on year. As a result prices should steadily rise, thus increasing the 'pull' of Arctic oil.

the case (Reuters, 2007; Kliewer, 2007), as do the increased licensing in the Barents Sea due to resolution of the long-standing border dispute between Norway and Russia.

1.5. Oil and sea ice

Depending on the season and surrounding sea ice conditions an accident, whether it be a pipeline breach, blowout, shipping accident or other, could spill oil on, under, or into the waters surrounding the sea ice. Whilst a spill could happen at anytime of the year or sea ice cycle most Arctic marine activities, at present, are concentrated around the summer months. If a spill is not cleaned up immediately, then we move into the difficult winter freeze-up period and beyond.

When oil is released in the water column, it rises towards the surface in a conical shaped plume. The rising oil tends to be unstable, and breaks in to small spherical particles of about 1 cm in diameter or less (Norcor, 1975). Upon reaching the underside of the ice it flows preferentially towards regions of thinner ice, accumulating in interconnected depressions under the ice as it spreads (Fingas and Hollebone, 2003, Wilkinson et al., 2007).

If a spill occurs during a time when the ice is growing then sea ice will form a lip around the perimeter of the oil before eventually encapsulating the oil within the ice matrix (NORCOR, 1975); forming what is known as an oil sandwich. Once encased in the sea ice there is little opportunity for the oil to naturally weather. Field and laboratory tests reveal that encapsulated oil is released in the spring/ summer melt period by either vertical migration of oil through the ice and its brine channel system, or through the ablation/melt of the ice surface downwards (Fingas and Hollebone, 2003). Upon reaching the surface the oil will substantially reduce the albedo of the snow and ice surface. Being dark the oil will absorb solar radiation and cause accelerated melting on the ice surface (Lewis, 1975).

The sea ice conditions found in the broken pack of the marginal ice zone could be more challenging as oil may be located under the ice, within the ice, on the surface of the ice and within the waters surrounding the sea ice. Oil on the surface will be "herded" downwind, whilst oil trapped under or within the ice will move with the ice. This could be in a different speed and direction to the surface water. This scenario is particularly challenging as each individual floe has a different surface and sub-surface shape and, they move differentially to each other. The result is an ice field whose concentration is continuously changing as a function of the ever-shifting wind and current field. Floes may come together squeezing the oil between them, or drift apart allowing to oil to spread out over the sea surface. Modelling studies by Venkatesh et al. (1990) suggested that for low sea ice concentrations (less than 30%) oil behaved as in open water, and for ice concentrations higher than 30% the oil moved with the ice.

Whilst oil spills under an ice cover spread much slower, occupy a smaller area than an open ocean spill, and are slower to weather they do present complex challenges to the modelling of the fate of oil spills as well as the technologies to detect, monitor and recover the oil spilled in the ice-covered seas.

1.6 Purpose of oil spill response in ice-covered waters

The essential point of undertaking any oil spill response is that it should reduce the amount of damage done to ecological resources and to human-use activities (fishing, hunting, tourism etc.) that could be caused by spilled oil. The effectiveness of oil spill response techniques could be then judged against the 'no response' cases by the degree to which the overall damage is lessened by conducting the response. It is therefore necessary to know which resources, both ecological and socio-economic, are likely to be damaged by the spilled oil at a particular location so that the appropriate response strategy and methods can be used to minimise the damage that could occur.

1.7 Ecology of ice-covered waters

It is obviously not possible to provide comprehensive descriptions of the many and varied coastal and marine habitats present in the Arctic and other areas of the world with "ice-covered waters". However brief overview is given to indicate some of the ecological resources that would need to be taken into account in any oil spill contingency planning is given in Section 5.3..

1.8. Why should Europe care?

Commercial investment in the Arctic could potentially reach $100bn or more in the coming decade with oil and gas, mining and the shipping industries being the biggest drivers (Lloyds, 2012). Moreover the latest assessment of undiscovered oil reserves held within the Arctic showed that 60% of the reserves were held in only six small regions (Gautier, et al., 2009), four of which are essentially European i.e. lie within the territorial waters of Norway and Denmark (Greenland).

The EU is well aware of the importance of the Arctic environment as well as the substantial differences that presently exist across the different Arctic states with respect to their regulatory regimes and standards. Consequently one of the EU's Arctic policy objectives (EU, 2008) is to

'support for the exploitation of Arctic hydrocarbon resources should be provided in full respect of strict environmental standards taking into account the particular vulnerability of the Arctic. The EU edge in technologies for sustainable exploitation of resources in polar conditions should be maintained.'

With opportunities comes risk and the environmental and economic consequence of a large oil spill in the Arctic are likely to be greater than in other regions of the world and therefore good governance, high international standards and best practices, and comprehensive but responsive regulatory regimes are in everyone's interest. For companies to work safely, sustainably and successfully in the Arctic a comprehensive understanding of risk management is fundamental (Llyods, 2012).

The vast majority of the sea ice and water leaving the Arctic, either through Fram Strait (the majority) or the Nares Strait/Canadian archipelago system, directly enters the north Atlantic. This implies that any oil spilled in the Arctic Ocean, if not cleaned up immediately, will eventually enter the north Atlantic, a region of huge economic importance to Europe. Closer to Europe however are the seasonally ice infested waters of the Baltic, which is considered an EU ocean (see http://eu.baltic.net/). These waters could be the most likely place for the first major oil spill under ice given that the Baltic (Gulf and Bay of Bothnia) is the world's most heavily trafficked sea-route with a seasonal ice cover. Although this is not mainly oil-tanker traffic, it has a large number of ships carrying their own fuel and oil. In recent years however, Russia has been rapidly increasing its oil export from the St. Petersburg regional ports, and during the winter these vessels pass through the ice in the Gulf of Finland. It is imperative that Europe takes the lead in oil-spill research and contingency planning for ice-covered waters.

There are few topics that divide opinion as much as exploitation of non-renewable resources in the Arctic, especially exploitation and transport of hydrocarbons. As a result a broad range of stakeholders such as industry, governmental and inter-governmental agencies, policy makers, the public, and NGOs have an interest in the topic both here in Europe and beyond.

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2. Oil-ice interaction, weathering and modelling

by

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2.1. Introduction.

The introductory section to this report paints a picture of an Arctic that is changing both climatically and economically; an industrialisation of the Arctic if you wish. Given the combination of the Arctic climate change scenarios, the need for natural resources and the very competitive Arctic shipping routes it seems inconceivable that human activity in the ice-covered waters of the Arctic will not increase significantly in the years to come.

The renewed interest in commercial activities in the Arctic marine environment, combined with a reduction in the extent and thickness of sea ice and the recent failings that lead to the devastating oil spill in the Gulf of Mexico have prompted industry and its regulatory agencies, governments, and NGOs to look at all aspects of Arctic oil spill countermeasures with fresh eyes. This section of the report focuses on modelling the fate of oil in the ice-covered sea.

The oil spill modelling community is well versed in the fate of oil within warm water environments. Complex models have been developed that use oceanographic, atmospheric and weathering variables to determine both the trajectory and fate of an oil spill in the open ocean. It is generally accepted that these complex models are well established and do a reasonable job. However similar modelling scenarios in the presence of sea ice is much more uncertain (Johansenet al., 2005). This is understandable, as most of the ship traffic and hydrocarbon exploration and exploitation to date has occurred in the 'warm' seas, far away from floating ice. Given that 'fact-finding' commercial shipping is already transiting the Northern Sea Route, and that drilling has already been performed off the west coast of Greenland in 2011 (and will commence in the Beaufort/Chukchi Sea region in 2012), accurate and reliable models on the fate of oil in ice-covered seas are needed now more than ever.

The main mechanisms which govern the fate of an oil slick in a warm ocean are spreading, evaporation, dispersion, emulsification, sedimentation and biodegradation. Many of these processes act simultaneously and have feedbacks that induce both a chemical and physical change to the properties of the oil. Furthermore the relative importance of each process is time dependant. From figure 2.1 we can see that evaporation, dispersion, dissolution, oxidation, emulsification and spreading are most important during the early stages of a spill whilst the sedimentation, biodegradation processes are more important in the longer term. An understanding of the way in which these multi-faceted weathering processes interact temporally and spatially is essential when modelling the changing characteristics of an oil during the lifetime of a slick at sea (ITOPF).

In the following subsections we explain the main processes involved in determining the fate of oil on the open ocean. Whilst in general the main mechanisms that govern the fate of an oil slick at sea are similar in the ice-covered seas, there are significant and important differences; for example the cold temperatures change the physical properties of the oil dramatically, evaporation is limited when oil is trapped under ice, and the spread of oil under ice is very different to its open-water counterpart. For this reason we include a description of each weathering process along with an explanation of some of the considerations or processes that need to be explored in order to better understand, and hence model, the fate of oil in ice-covered waters.

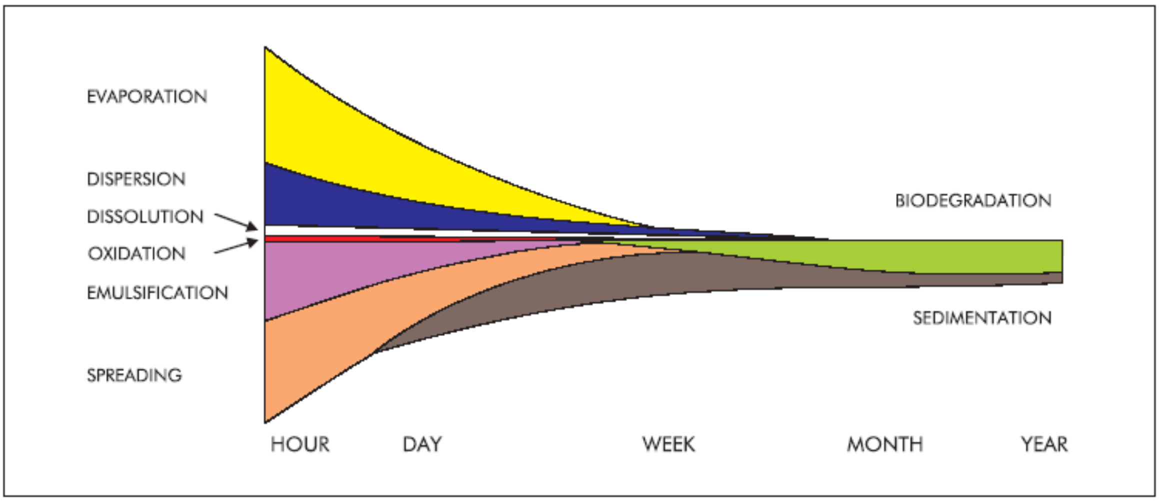

Figure 2.1. Schematic representation of the fate of a typical medium crude oil, spilled under moderate sea conditions. This figure displays the changes in the relative importance of weathering with time. The width of each band indicated the importance of the process. (from ITOPF Technical Information Paper)

2.2. Oil properties

Crude oils of different origin vary widely in their physical and chemical properties, whereas many refined products tend to have well-defined properties irrespective of the crude oil from which it was derived (ITOPF). The properties of residual products such as intermediate and heavy fuel oils also vary considerably.

The main physical properties which affect the behaviour and the persistence of an oil spill at sea are specific gravity, distillation characteristics, viscosity, wax content, and pour point. All are dependent on the chemical composition of the oil. An example of the importance of the composition can be seen in figure 2.2. For more information on the physical and chemical properties of various oils and emulsions the reader is referred to http://ec.europa.eu/echo/civil_protection/civil/marin/cis/mpcis04_oil_properties_en.htm

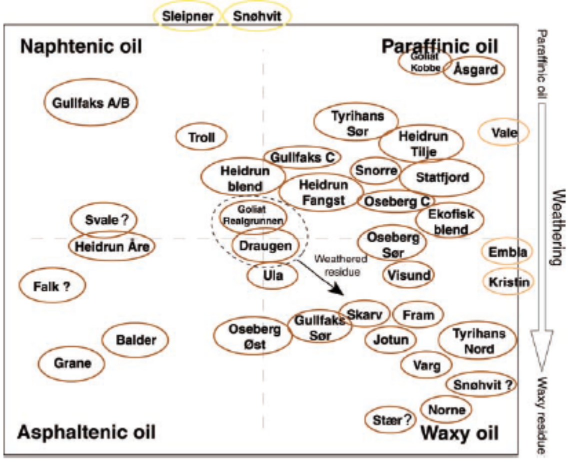

Figure 2.2 Illustration of different cruse oil properties based on weathering studies performed by SINTEF (JIP)

- Specific gravity: Is the relative density of oil in relation to pure water. Most oils have a specific gravity 0.8 gcm^{-3} and thus are lighter than sea ice that has a density of around 0.9 gcm^{-3}, and seawater that has a specific gravity of around 1.025 gcm^{-3}. Therefore fresh oil will rise to the sea or ice surface if it can. Furthermore the density can often give a general indication of other properties, for example oils with low densities tend to contain a high proportion of volatile components and generally have a low viscosity.

- Wax content: Oils with a wax content greater than about 10% tend to have high pour points. High wax contents also help to stabilize water-in-oil emulsions. Some light oils behave more like heavy oils due to relatively high wax content.
- Pour point: The temperature below which an oil will not flow. If the ambient temperature is below the pour point the oil will be solid-like and not spread over the sea surface as a film.
- Distillation characteristics: As the temperature of the oil is raised different components reach their boiling points and are distilled off. This determines the volatility of an oil and controls the rate and extent of evaporation. The distillation characteristics are displayed as percentage volumes that distil off within set temperature ranges.
- Asphaltene content: Asphaltenes are tar-like substances that enable oil to form a water-in-oil emulsion. Oils with asphaltene contents greater than 0.5% tend to form stable emulsions. These emulsions can contain up to 80% water by volume and are generally extremely viscous.
- Viscosity: The viscosity of an oil is its resistance to flow. High viscosity oil flows with difficulty, while oil with low viscosities are highly mobile and spread quickly over the sea surface. It is important to remember that the viscosity of oil increases as temperature decreases and therefore sea and air temperatures are important in determining the viscosity of an oil spill.

2.3. Processes that govern weathering in the open ocean

The combination of physical and chemical processes that transform the properties of the oil after a spill has occurred are collectively known as weathering. These changes start from the moment the oil makes first contact with seawater. There are seven natural processes that are important for understating the fate of oil in the marine environment. These are:

1. Evaporation
2. Spreading
3. Natural dispersion
4. Emulsification
5. Biodegradation
6. Oxidation
7. Sedimentation

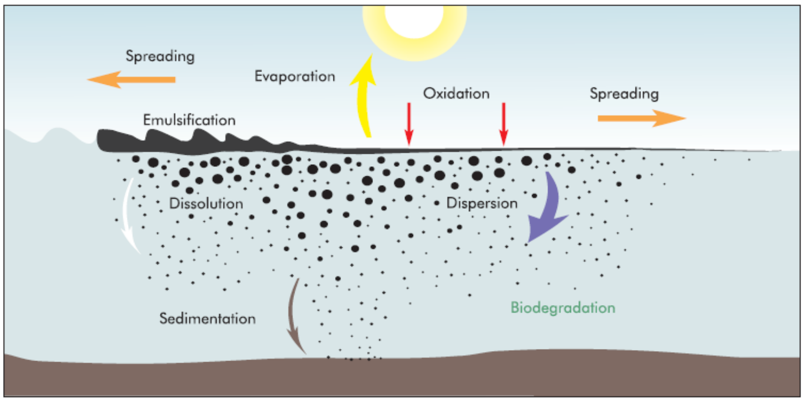

Figure 2.3 Weathering processes acting on spilled oil under 'warm' open ocean condition (ITOPF)

And are represented schematically in figure 2.3 and explained in the following sections.

2.3.1 Evaporation:

Evaporation is probably the most important weathering process for the removal of oil at sea. During the first 48 hours of a spill a considerable part of oil transforms into the gaseous phase and results suggest evaporation can be responsible for the loss of one- to two-thirds of an oil spill's mass, although over time this loss rate decreases rapidly (US Congress, 1991).

The evaporation rate of oil on the sea surface is a function of both the oil type and environmental conditions. Controlling parameters include the physico-chemical composition of the oil, the surface area of the slick, wind speed, air and sea temperatures, sea state (waves), and the intensity of solar radiation (Payne and McNabb, 1984). When a spill first occurs the evaporation rate will be very high because of the large surface area to volume ratio. As the volume of oil in the water increases over time the evaporation rate will decrease because the ratio between surface area and volume decreases.

Light oils, such as gasoline, aviation fuel and diesel, usually weather rapidly when exposed to the air, whilst heavy fuel oils only loose a small proportion of their volume by evaporation (EPPR, 1998). This is because denser liquids are generally slower to evaporate. One of the consequences of evaporation is a reduction in oil volume (through the loss of volatile components and water-soluble hydrocarbons), but an increase in oil viscosity and density of the remaining oil. These changes influence other weathering processes such as the natural dispersion, emulsification, dissolution and sedimentation (Sebastião and Soares 1996). If oil is transported away from the surface of the ocean the evaporation rate significantly decreases or stops.

Arctic considerations for evaporation:

Low temperature: For a molecule of a liquid to evaporate it must have sufficient kinetic energy to overcome liquid-phase intermolecular forces. Since the kinetic energy of a molecule is proportional to its temperature, evaporation proceeds more quickly at higher temperatures. Evaporation will most likely occur at a slower rate in the Arctic. Hänninen and Sassi, (2010) found that under calm, warm conditions (0° to 5°C) between 5% and 20% of diesel fuel evaporated in 2 days, whilst under colder conditions (-20° to 0°C) it took over twice as long (4 to 5 days).

Low surface area: A spill that occupies a large surface area will evaporate faster than a spill confined to smaller regions. This is an important consideration in ice-covered seas as depending on the season the amount of open water available will vary considerably, from almost none in winter to an open sea in some areas of the Arctic Ocean in summer. Furthermore during the spring break-up period transient open-water regions develop around the floes in the marginal ice zone. The sizes of these open-water areas are constantly changing, mainly as a function of wind strength and direction. For example an on-ice wind will close the pack, whilst and off-ice wind will open the pack up. In general the amount of open water available for the oil to spread over will be limited in ice-infested waters.

Access to the atmosphere: Depending on the ice type and where the oil is located within an ice cover the availability of the oil to interact with the atmosphere may be limited. For oil trapped under or encapsulated within a solid ice cover the evaporation rate may fall to near zero. Whereas under new ice, frazil or nilas for example, some exchange with the atmosphere may be possible. Some additional communication may occur during the summer months when the oil begins to migrate up towards the surface of the sea ice.

2.3.2 Spreading

The spreading of oil released on the sea is probably the most recognisable of all the weathering processes. The spread of oil over the sea surface is gravity dominated flow that is governed by oil viscosity, the surface tension of water, and the volume of oil spilled. Primarily its pour-point must be lower than the ambient seawater temperature, if not the product will solidify immediately or shortly after contact with the ocean (Sebastião and Soares 1996). Generally low viscous oils spread more quickly than highly viscous oils.

Under fully quiescent conditions the oil split on the ocean's surface will form a coherent, circular slick. True calm conditions do not exist and therefore the spread of oil on the ocean's surface will be influenced by a combination of meteorological and oceanographic factors. These are predominately the strength and direction of the wind, the current and wave radiation pressure. Oil spills can spread over several hundred kilometres in a few days and therefore the availability of accurate wind, wave and current fields at the appropriate temporal and spatial scale are crucial to model a slick's trajectory (ITOPF). The surface area of a spill strongly influences both the evaporation rate and dispersion. It should also be mentioned that the thickness of oil within a slick does vary considerably (Sebastião and Soares 1996).

Wind, currents and wave action will elongate the slick, but turbulence is needed to break the slick up in to smaller discrete slicks. Wind-induced turbulence is normally present within the upper surface layer of the ocean; whether it is in the form of small wind ripples or ocean swell. The amplitude, speed and period of these waves is a function of the direction, strength and duration of the wind as well as the distance of open water the wind blows over (the fetch). Waves, especially breaking waves, play a significant role in the break-up of an oil slick (see also natural dispersion).

Arctic considerations for Spread:

Data sparse: Accurate current, wave and wind-field data are difficult to obtain and poorly understood in the Arctic. This suggests that accurate prediction of the trajectory of an open-ocean slick could be particularly difficult during the ice-free months.

Under ice oil spread: The spread of oil under sea ice is very different to that on the sea surface. For example it will not be influenced by the wind directly, but will preferentially flow along the ice bottom towards regions of thinner ice, accumulating in interconnected depressions under the ice as it spreads. Because of this characteristic under-ice roughness dominates the oil's behaviour, although the rate at which it is introduced, the viscosity of the oil, the surface oil-ice-water interfacial tensions all play a role in determining the rate at which oil spreads under sea ice (Wilkinson et al., 2007). Much work is still needed in this field, as most existing oil-under-ice models are inadequate because they are unable to replicate the complexity or uniqueness of the bottom topography of sea ice (Fingas and Hollebone, 2003; Wilkinson et al., 2007). We have very little understanding of the spread of oil under most ice types and ridges will complicate the matter further.

Under ice currents: Experimental results have shown that the minimum threshold current to move crude oil under smooth sea ice was in the order of 0.15 m/sec increasing to approximately 0.21 m/sec under slightly rougher ice (Cox and Schultz, 1980). The current felt by the ice bottom varies depending on the direction and speed of the ice and the direction and speed of the ocean currents directly underneath the ice. Accurate current and *ice speeds are difficult to simultaneously obtain, Furthermore, our knowledge of the role of under ice turbulence in the movement of oil is almost non-existent.*

Sea ice drift: Other than the small amount of sea ice that is fixed to the shore, known as land-fast ice, the sea ice in the Arctic Ocean is constantly on the move. Therefore any oil spill emanating from a fixed location (sub-sea) such as a shipping accident, pipeline rupture or blowout will have a steady stream of ice drifting over the release point. The speed the ice moves over the release point will influence the amount of oil that reaches the ice, and its subsequent spread over the ice bottom. Over time the oil contaminated floes could drift several hundred kilometres from where the oil was released. The divergent and convergent nature of sea ice drift suggests the tracking of contaminated floes will my pose a problem.

Leads: Oil slicks on the ocean surface are open to wind forcing. As a result oil within a lead or polynya will be blown down-wind until it encounters an ice floe. If the oil can not work its way around the floe it will gather in thicker amounts against the floe until it deepens to such an extent that it becomes thicker than the floe. At this point the oil will flow underneath the ice. If the blocking floe moves or rotates oil would escape by flowing through any open-water, downwind path that was available, and the spread of oil under the ice will cease. When a lead closes it is not clear if the oil will be squeezed onto the surface of the floe or underneath the floe.

Ridges: Deformed ice, such as ridges or rubble fields, may act as barriers to the movement of oil under sea ice. A ridge is made up of a disorderly collection of ice blocks and as such may not actually form an impenetrable barrier to the oil, but may allow the oil to percolate through the holes between the adjacent blocks. The 'porosity' of a ridge is not presently known, or if this 'porosity' changes over time. If so, an older ridge may influence the flow of oil differently than a newly formed ridge.

2.3.3 Natural dispersion

Natural dispersion is the process by which small droplets of oil become incorporated in the upper water column through upper ocean turbulence such as breaking waves. The redistribution of these droplets away from the main slick can account for a significant reduction in the volume of oil within the original slick. Unlike evaporative loss it does not lead to changes in the physio-chemical properties (Sebastião and Soares 1996), however the increased surface area of the droplets can stimulate processes such as biodegradation, dissolution and sedimentation (ITPF).

The amount of wave-induced dispersion is largely dependant on properties (viscosity) of oil and the wave energy available. Breaking waves convert the oil from a layer on the sea surface into a range of different sized oil droplets dispersed within the upper water column (BoHaSA, 2011). The largest oil droplets float back to the surface where they may coalesce with other droplets to form a small slick, whilst the smaller droplets may become distributed within the upper water column. Under shallow water conditions these droplets may interact with the ocean floor (Turrel, 1994).

High viscosity and dense oils, such as heavy fuel oils, do not readily form droplets and as a result they do not naturally disperse to any significant degree under most sea conditions. Low viscosity oils in a high sea state disperse most quickly.

Arctic considerations for Natural dispersion:

<u>Open ocean waves:</u> In the past, most of the Arctic Ocean remained ice-covered all year round with limited open water present. Because of this reduced fetch very little wave energy was traditionally present. However the much-reduced summer ice cover we see today has produced a larger fetch, generating higher amplitude waves with longer periods. The changing wave-field in summer suggests enhanced dispersion of oil during the ice-free summer months may be possible. Although due to the cold temperatures dispersion may not to be as efficient as in warmer seas.

<u>Ice-wave interaction:</u> An ice cover is very efficient at damping out ocean waves (Wadhams, 2000). As a result breaking waves are almost non-existent within an ice-covered sea. They may be found however in the region near the ice edge. It is not expected that natural dispersion will pay a large role in the fate of oil within ice-covered seas

2.3.4 Dissolution

The rate and extent to which oil dissolves in seawater depends upon the properties of the oil, water temperature, turbulence, the spreading of the slick, and the degree of natural dispersion. It is the most volatile components that are prone to dissolution, but these are the same compounds that are lost up to 1,000 times faster by evaporation (ITOPF). This suggests that dissolution does not play a significant role in the weathering of oil in the open ocean environment. Heavy components of crude oil are virtually insoluble in seawater, whilst lighter compounds are slightly more soluble.

Arctic considerations for Dissolution:

<u>Access to the atmosphere</u>: The evaporation rate for oil trapped under or encapsulated within a solid ice cover may fall to near zero. Under these circumstances the most volatile components will remain in the oil and therefore dissolution may play a more dominant role in the weathering of oil in ice-covered seas. For example while the oil is encapsulated in the ice some water soluble oil compounds can be dissolved with the brine and released into the ocean during ice growth/brine drainage events (Faksness and Brandvik, 2008).

2.3.5 Emulsification:

An emulsion is a mixture of two (or more) liquids that are normally incapable of being mixed, such as oil and water. The critical factor for oil to emulsify is the amount of asphaltenes present, whilst the stability of the emulsion is related to the presence of wax crystals (Sebastião and Soares 1996). Over time asphaltenes can precipitate out to form an elastic-like layer around water droplets that have become entrained in the oil by turbulence (BoHaSA, 2011). The more viscous the oil the slower it takes up water. Stable emulsions, containing as much as 80% water, are more voluminous, dense and extremely viscous (often semi-solid) and may remain emulsified for significant periods of time. Less stable emulsions may separate out into oil and water if heated by sunlight under calm conditions (ITOPF).

ITOPF suggests that the formation of water-in-oil emulsion reduces the rate of other weathering processes and is one of the main reasons for the persistence of light and medium crude oils on the sea surface.

Arctic considerations for Emulsification:

Reduced turbulence in ice: Because the emulsification rate is a function of turbulence the reduced wave energy in the ice-covered seas should decrease the emulsification rate of oil.

Enhanced turbulence open water: The increase in open water during the summer melt period suggests an increase in the turbulence within the upper water column (mainly wave driven). This increase in turbulence increases the likelihood of the emulsification of oil during the open water season.

Cold temperatures: The stability of emulsions usually increases with decreasing temperature. This suggests in cold water environments emulsions may be more stable.

2.3.6 Biodegradation of oils

Biodegradation refers to the natural process whereby bacteria or other micro-organisms alter and break down organic molecules into other substances, such as fatty acids and carbon dioxide (U.S. Congress, 1991). Oil contains aromatic compounds that are toxic for most life forms, however certain marine organisms can alter and/or metabolise different compounds that are present in oil (Bence et al., 1996). These organisms include bacteria, moulds, yeasts, fungi, unicellular algae and protozoa.

Several factors influence the biodegradation rate in the ocean, these include surface area of the spill, ocean temperature, the nutritive supply (e.g., nitrogen, phosphorus, potassium), the oxygen supply (although biodegradation can occur under anoxic conditions), oil type, and the degree of weathering (BoHaSA, 2011), as well as the abundance and species of oil-degrading micro-organisms. Because the microbial community live in the seawater biodegradation can only take place at an oil/water interface. Consequently the production of oil droplets may enhance biodegradation as the surface area available increases. During the oil biodegradation process the properties of the oil change because the various compounds within the oil are more or less susceptible to biodegradation (e.g., Goodwin et al., 1983). Some of the main findings of a US Congress report on Bioremediation for Marine Oil Spills (U.S. Congress, 1991) include:

- The usefulness of bioremediation for marine oil spills is still being evaluated, and their ultimate importance relative to other oil spill response technologies remains uncertain.
- Bioremediation has not yet been demonstrated to be an effective response to "at sea” oil spills.
- No significant adverse impacts related to the use of bioremediation technologies have been identified in recent field applications.

In the long term it is the microbial communities that transform and degrade the oil.

Arctic considerations for the Biodegradation of oils:

Unknown: The impact of the biodegradation of oil in ice-covered seas is presently undetermined. Given that the oil may be contained under the ice, or encapsulated within the ice itself, for extended periods of time there is a role for the micro-organisms in the weathering process. Modelling this process will not be trivial.

2.3.7 Oxidation

Under the influence of solar radiation hydrocarbons can react with oxygen to form either soluble products or persistent tars. It is suspected that the overall effect of oxidation on is minor compared to that of other weathering processes. This is because under intense sunlight a thin oil of film break down gradually, usually less than 0.1% per day (ITOF). Very viscous oils or water-in-oil emulsions tend to oxidise to persistent 'tar ball' like structures that usually consist of a solid outer crust of oxidised oil, surrounding a softer, less weathered interior.

Arctic considerations for the Biodegradation of oils:

Variable solar input: The amount of solar radiation varies with latitude and season, from 24-hour darkness during the winter months (negative effect), to 24 hour daylight in summer (positive effect). Furthermore oil trapped under ice will be 'shaded' by overlying sea ice and associated snow cover (negative effect). Therefore the season and location of the spill (open water or under ice) will determine the influence oxidation has on the weathering of oil.

2.3.8 Sedimentation

The weathering process can alter the specific gravity (density) of an oil to a point where it becomes neutrally buoyant or even sinks, for example some heavy crudes. Most heavy fuel oils and water in oil emulsions, have specific gravity close to that of sea water (ITOPF). Other sedimentation methods include oil droplets adhering to suspended material within the water column, and the ingestion of oil by marine organisms subsequent incorporation in faecal pellets. Both these methods produce pathways for oil to sink to depth where it can be preserved for a substantial time period. It is not clear the extent of sedimentation that occurs during the weathering process.

Arctic considerations for the Sedimentation:

Density changes: Over an annual cycle the salinity (analogous to density for Arctic waters) of the upper ocean changes significantly. The melting sea ice and river input lowers the surface density of the ocean during the summer season, whilst during the winter months the upper waters become denser through cooling and brine rejection during sea ice growth. Any oil that is around the density of 'normal' seawater will sink down to their density-derived depth during summer, only to reappear at the ocean surface or under the ice in the winter months. It is therefore important to know the specific gravity of the oil throughout the weathering process.

Particulates: Away from regions around the river mouths the amount of suspended particulate matter in the upper water column will be limited. However during the spring and summer months phytoplankton blooms occur within the Arctic Ocean. Oil droplets that are present in the water column may adhere to these small particulates or be ingested by marine organisms grazing on the phytoplankton. Through this method oil could be transported between different levels of the food chain. Depending on the season an oil spill occurs the biological impacts could be very different.

2.4. Potential damage that can be caused by spilled oil

It should be remembered that it is not the spilled oil is not the actual problem; it is the damage that the spilled oil causes to the ecological resources and habitats that are present that needs to be responded to. As will be seen within this report, the presence of ice and the other environmental conditions that prevail in the Arctic (and other areas with seasonal ice on the sea) will alter the behaviour of the spilled oil and can limit the feasibility, or effectiveness of, the various oil spill response techniques that are available. In order to assess the probability of success of using any of the available oil spill response techniques at an oil spill that could occur in ice-covered waters, the likely outcome first need to be compared to that of an identical oil spill occurring in temperate, ice-free waters. This is explored further in Section 6.1

2.5. Oil ice interaction

It is clear that the fate and behaviour of oil spills on the sea surface is complex. It is also clear that it is fundamentally important to understand

(a) the processes involved with respect to the environmental conditions encountered
(b) how these processes interact both temporally and spatially to alter the properties and behaviour of oil with time.

By doing so models can be developed to predict how an oil spill will weather and drift over a period of time, given a specific set of conditions. The overall aim is to be able to predict the overall fate and potential impacts of a slick in ice coved waters, whatever the environmental conditions or oil type involved. Much work has been performed on oil spills in open waters, and we are starting to elucidate the intricacy of the spread and weathering of oil when sea ice is involved.

From the previous section we can see that the speed, timing and relative importance of the seven natural weathering processes depends on factors such as the properties and volume of oil spilt, the prevailing weather and sea conditions, as well as the abundance and species of oil-degrading micro-organisms that are present. Where the oil is located with respect to the sea ice (and the ice type itself) significantly changes the weathering profile of the oil.

What makes the problem particularly difficult for an oil spill in an ice-covered sea is the plethora of environmental scenarios that could play out, from open water to broken pack to compact pack, from young ice (i.e. frazil, pancake, nilas) to multiyear ice, from growing ice to melting ice, from total darkness to 24-hour light, and from exceptionally cold temperature to moderately cold temperatures.

A schematic of the main oil-ice interaction and weathering processes for open water conditions, summer ice conditions and winter ice conditions can be found in figure 2.4. Not shown in this figure is a further scenario whereby heat contained within the oil, from rising blowout plume for example, inhibits ice formation and keeps an area of open-water ice free from late summer, and throughout the following winter (Lewis, 1976).

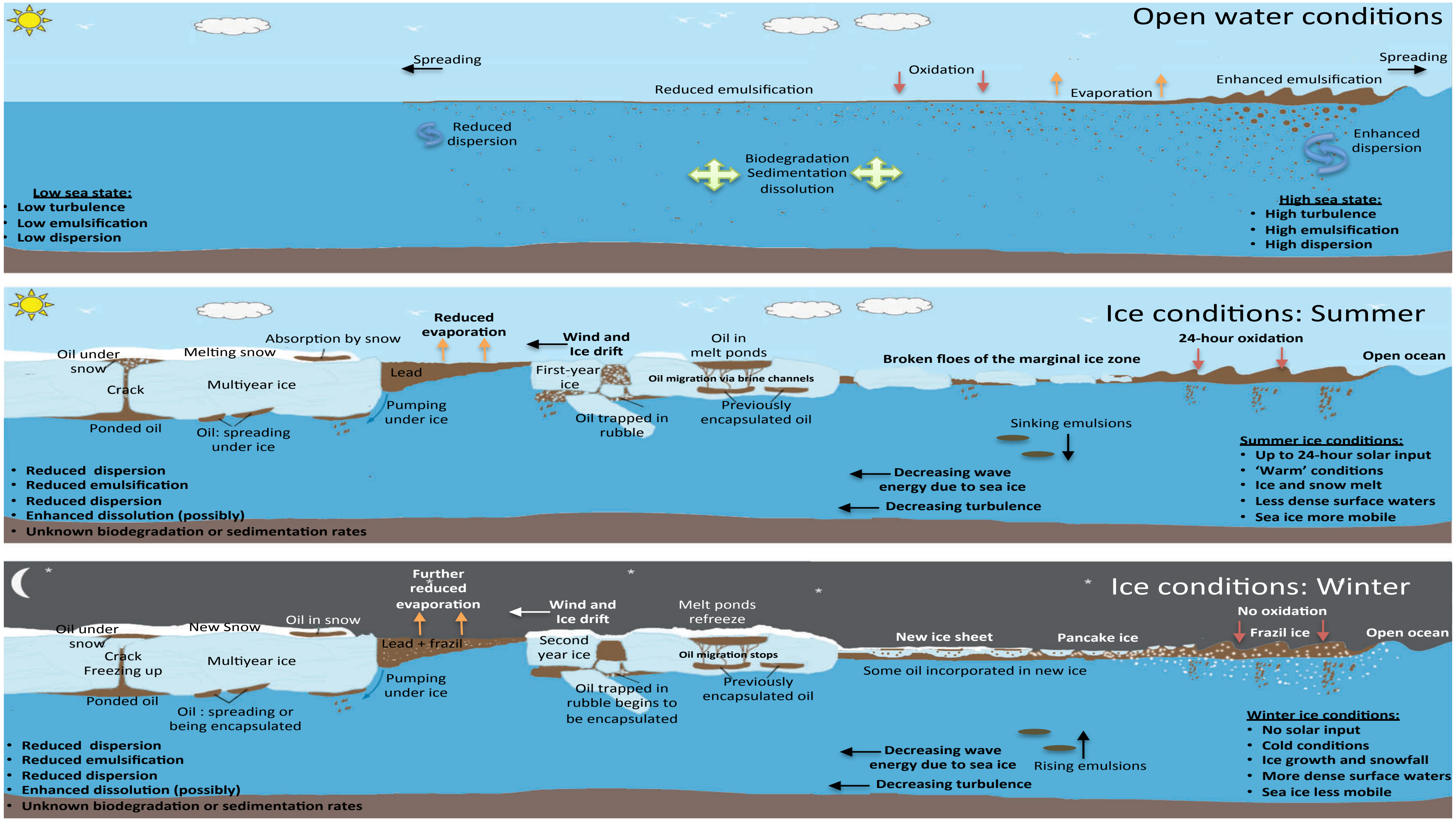

Figure 2.4 Sequence of the main oil-ice interaction and weathering processes in (top) open water conditions, (middle) ice conditions in summer and (bottom) ice conditions in winter (based around original figure by Bobra and Fingas, 1986). The main environmental factors influencing

2.6. Oil, sea ice and modelling.

When oil is spilled on the ocean's surface it spreads to form a slick whose spread is due to the balance between the forces of gravity, viscosity and surface-tension. The trajectory or drift of the slick is governed by the forces associated with currents, winds and waves (Wang et al., 2005). A comprehensive review of open-ocean fate and trajectory models can be found in ASCE or Reed et al. (1999).

The origin of oil spreading models stretches back to the 1960s with the pioneering work of Fay (1969). Soon after these seminal papers research and modelling began to look at the problem of the spreading of oil under a solid ice. Work began in the early 1970s with models by Glaeser and Vance (1971), Hoult et al. (1975) as well as a large body of experimental work linked to the Beauport Sea Project. These early semi-empirical models used gravity-inertia, gravity-viscosity, and interfacial tension-viscosity to describe the spread of oil. In the 1980s simple predictive models were able to describe the motion of oil under the ice surface by entering key parameters such as oil properties (i.e. viscosity, density, interfacial tension), spill duration, flow rate under ice, oceanographic properties (i.e. current speeds and water density) and under ice roughness (Woodspoon et al., 1985, Comfort, 1987). These models assumed that there were these parameters did not vary over time, that oil moved with the ice, and no weathering of the oil occurred.

Various other advances have been made over the years. These include Venkatesh et al.'s (1990) efforts to use empirical methods to determine the spread of oil under various broken ice scenarios, and Wang et al. (2003) developed a series of formulae to describe the spreading of oil under ice with different ice-coverage regimes. Yapa and Chowdhury (1990) using a simplified form of Navier–Stokes equations for characterising the spread of oil under an ice cover. Venkatesh and El-Tahan (1992) developed new relationships for the viscosity of oil in cold water, and Izumiyama et. al. (2004) developed a set of theoretical derivations to estimate the area of oil under both smooth and rough ice sheets. As expected the governing equations of all these models are based on the conservation of momentum and the conservation of oil mass.

The sophistication of these models continues to improve, including the coupling of ice-hydrodynamic-oil models that have enabled sea ice dynamics, oil spill dynamics to be integrated with oil dispersion and weathering algorithms e.g. Skognes and Johansen (2004).

There is still work to be done; Reed et al. (1999) concluded that leads play a dominant role in impacting oil behaviour but are not incorporated in most models, and upon reviewing theoretical models of oil behaviour in ice conditions, Fingas and Hollebone (2003) suggested that all existing oil-under-ice models are inadequate because they are unable to replicate the complexity or uniqueness of the bottom topography of sea ice. Wilkinson et al., (2007) addressed the concerns of Fingas and Hollebone (2003) by obtaining accurate in situ data on the 3-dimensional shape of the underside of first year sea ice through the use of an Autonomous underwater vehicle with an upward-looking multibeam sonar. By coupling these data to a simple oil spill model an accurate appraisal of the potential oil holding capacity of first year sea ice was achieved (figure 2.5).

The following sections elaborate on the different regimes that can influence the fate of oil in ice-covered waters. These include the spread of oil under ice, encapsulation, oil migration, surface melt processes, distance from release point, mixed ice/ocean regions, and the weathering of oil in ice.

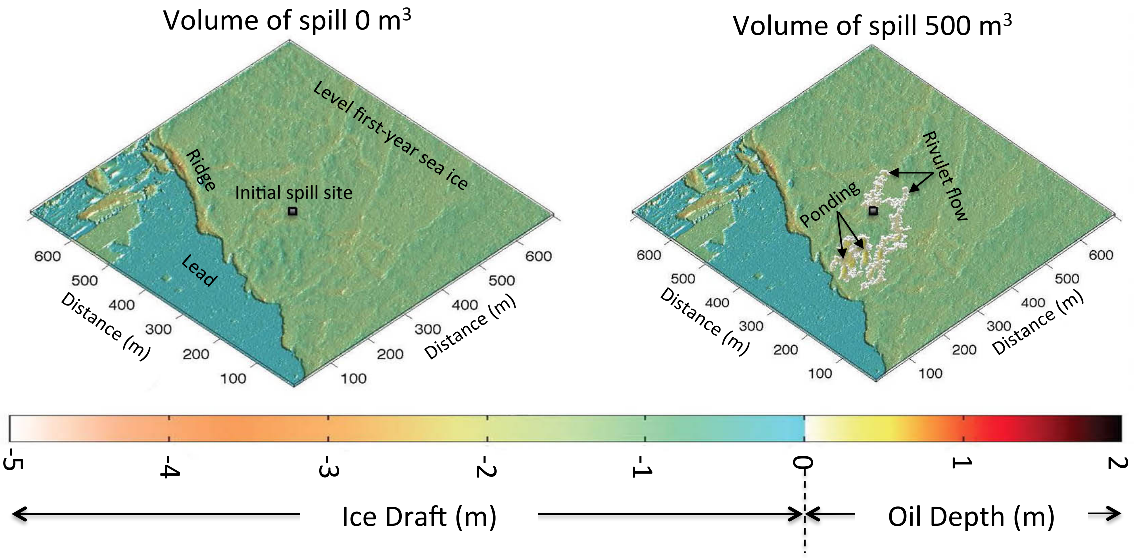

Figure 2.5. Before and after results from an under ice oil trajectory model run on real ice topography obtained from an upward looking multibeam sonar mounted on an autonomous underwater vehicle. **Left**: Ice conditions before oil spill applied. **Right**: Results after 500 m^3 of oil spilled at the black square region in the centre of the image. Oil spread shows both rivulet flow and ponding. Overall modal oil thickness under this level first year ice was just a few centimetres. (Figure courtesy Wilkinson 2012).

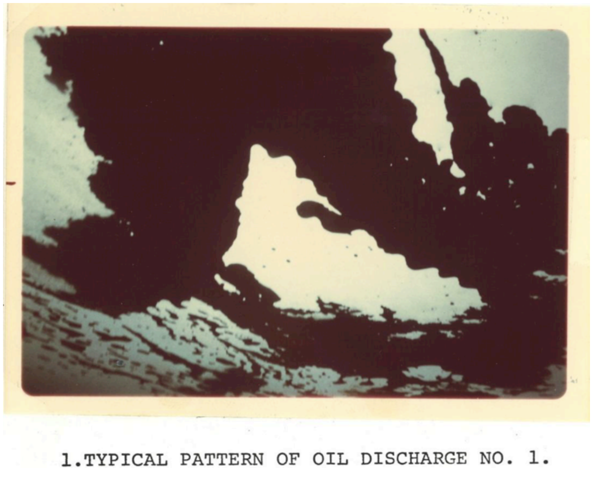

Figure 2.6 Oil forming small rivulets that move from one depression to the next. NORCOR oil under ice recovery tests Beaufort Sea, May 1975

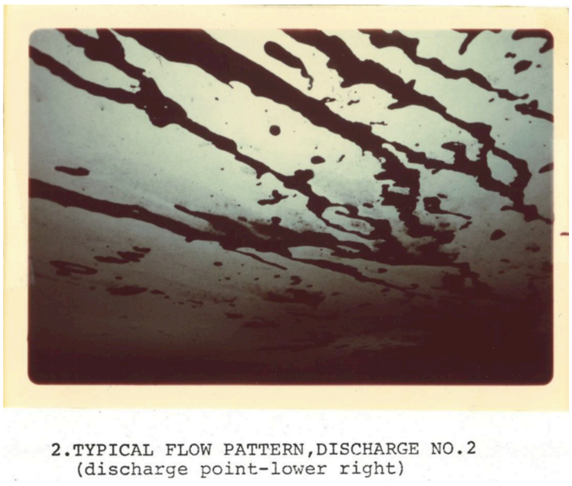

Figure 2.7 Oil gathers in depressions to form under ice larger rivers. Also visible in the image are areas of thicker ice remaining as 'clean' islands surrounds by oil. NORCOR, 1975.

2.6.1 Spread oil under ice

Oil, if more buoyant that the surrounding seawater, will rise through the water column breaking down into small droplets as it rises (Topham, 1975). At the underside of the ice most of these droplets will coalesce to form an oil slick. As the oil layer thickness builds up the slick will then move outwards from the central region due to hydrostatic pressure differences. Laboratory and in situ testing under sea ice have shown that this thickness is range 0.5 to 1 cm (Dickins et al., 1975, Keevil and Ramseier, 1975).

Moving radially outwards the oil will fill all available irregularities preferentially flowing towards regions of thinner ice. This movement will either be dominated by the oil spreading out in narrow rivulets (figure 2.6) or filling up deeper and wider depressions such as those seen in figure 2.7. When an individual depression is full, a rivulet of oil run will flow outward over the depression and into the next interconnected depression (Fingas and Hollebone, 2003, Wilkinson et al., 2007).

It is under-ice roughness the dominates an oil's behaviour, although the rate at which it is introduced, the viscosity of the oil, and the surface oil-ice-water interfacial tensions all play a role in determining the rate at which oil spreads under sea ice (Wadhams, 1976; Wadhams 1980; Malcom, 1979, Wilkinson et al., 2007). The direction of the flow of oil is a function of the under-ice topography, ice dynamics (if any), upper ocean turbulence and oceanic currents. Individual sessile drops or slicks are quite difficult to move due to "sticking friction" between the drop and the skeletal layer at the ice/water interface (Lewis, 1976). Tests to quantify the movement of oil due to oceanic currents have shown that the minimum threshold current to move crude oil under smooth sea ice was in the order of 0.15 m/sec increasing to approximately 0.21 m/sec under slightly rougher ice (Cox and Schultz, 1980).

2.6.2 Encapsulation

If a spill occurs during the ice growth season sea ice may form a lip around the perimeter of the oil pool, inhibiting the further horizontal motion of the oil. Results for Lewis, (1976) and Izumiyama et al., (2004) suggest that ice growth under the oil layer is reduced due to the insulating properties of oil compared to ice. If the transfer of heat from the ocean/ atmosphere to the ice-oil-ocean interfaces is sufficient for ice growth, the ice will continue to grow beneath the oil pool eventually completely encapsulating the oil within the ice matrix (NORCOR, 1975) and forming what is known as an oil sandwich (figure 2.8). This new ice sheet under the oil does not appear to be crystallographically connected to that above the oil pool.

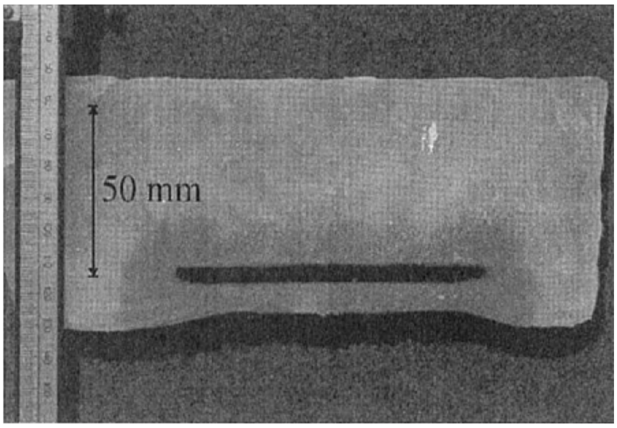

Fig 2.8 . Laboratory experiment showing the cross section of anoil-ice sandwich (Izumiyama et al., 2004)

In situ experiments by Lewis (1976) showed that it took about a week for ice to start to grow beneath the oil pool oil spilled under 160 cm thick ice (March in the Beaufort Sea). The encapsulation process would be quicker under thin ice, and may not happen at all under thicker ice. While the oil is encapsulated some water-soluble compounds of the oil may be dissolved with the brine and released into the ocean during ice growth (Faksness and Brandvik, 2008).

2.6.3 Oil migration

Under certain conditions oil can move vertically upwards through the sea ice; a process known as oil migration through brine channels. Field and laboratory studies reveal that encapsulated oil is released in the spring/summer melt period by either vertical migration of oil through the ice and its brine channel system, or through the ablation/melt of the ice surface downwards (e.g. Lewis, 1976, Martin, 1979). These methods transfer oil from within or under the ice to the ice surface or overlaying melt ponds. An example of both these processes at play can be found in Martin (1979). During this study Martin (1979) spilled oil under land-fast sea ice (of 1.5-2 m thickness) in February and April 1975 and by the end of May melt pools had formed on the ice surface and oil had began to migrate up to the surface. This upward migration of oil continued and the thickness of oil at the surface increased over time. Both processes are extremely important, but as yet no models have been developed to parameterise oil releases events through ice ablation and oil migration (Fingas and Hollebone, 2003).

2.6.3.1 Brine channel migration

As snow begins to melt on the sea ice surface the sea ice also begins to warm. As sea ice warms the connectivity of brine drainage channels increases, see figure 2.9, until the sea ice porosity allows the low-salinity melt-water to percolate through it. The through flow of melt-water removes the high-salinity brine contained in the interconnected brine drainage channels (Eicken, 2003), a process known as flushing. This flushing process occurs because the melt-water is not in hydrostatic equilibrium with the underlying waters, but is held by ice until both the porosity and connectivity of the channels increase to such and extent that it can flow through the brine drainage channels within the ice under the influence of gravity.

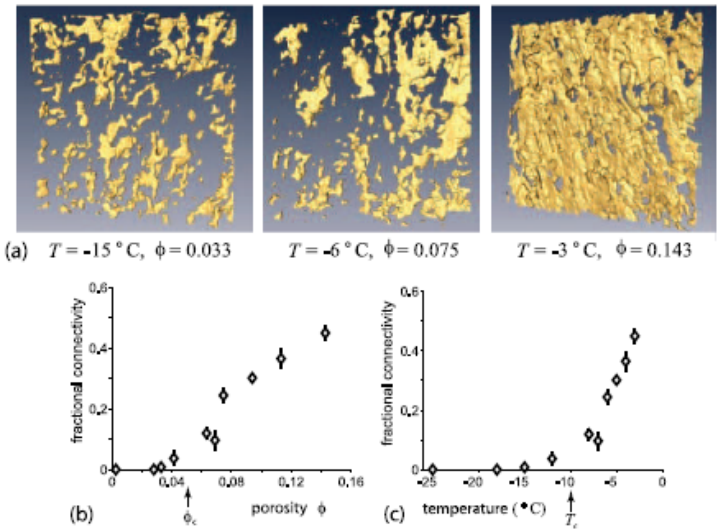

Figure 2.9: Images showing the thermal evolution of the brine connectivity (from Golden et al. (2007).
(a) X-ray computed tomography for sea ice (salinity 9.3‰) during a stepwise warming circle. Micro-scale morphology and connectivity seems to change dramatically from T = −6°C to T = −3°C
(b) and (c) Fractional (vertical) connectivity calculated as the proportion of brine inclusions intersecting both the upper and lower surface of a cylinder of height 8 mm and diameter 21 mm. T_c and ö$_c$ mark the percolation threshold predicted by a lattice model. Notice the connectivity increases as both ice temperature and porosity increase.

Recent laboratory tests have shown that melting sea ice allows two different modes for the upward transport of oil; the slower oil permeation through the fine scale pore network (pores and necks less than 0.1 mm), and the faster Poiseuille flow through brine channels (diameters 1-2 mm) (Karlsson, 2009). The brine drainage channels that flushed the brine from the sea ice now offer an escape route to the ice surface for the more buoyant oil. Laboratory experiments by Karlsson, (2009) suggest that sea ice is permeable for porosities of more than 5%, but it appears that oil movement is constrained to porosities of above 15 %.

Lewis (1975) point out that circumstances are entirely different for oil trapped under multi-year ice as there are no significant brine drainage channels except in the lower portion, which is growth from the immediately preceding winter. As a result the residence time of oil under multiyear ice may be significantly longer than that of first-year ice. At present most shipping lanes and exploration regions are in areas dominated by first-year ice.

2.6.4 Surface melt processes

Almost 90% of the sun's radiation is reflected back from new snow, about 50 % from sea ice, about 20 % from melt ponds and only around 6% from open water (Perovich, 1998). In contrast the albedo of an oiled snow/ice surface is in the range 8-10%. As a result any oil at the surface of the ice will absorb solar radiation and cause accelerated melting on the ice surface, therefore in a short time the oil will be floating in a melt pool of its own making (Lewis, 1975). This process will accelerate as more oil migrates to the surface. Through absorption of radiation the temperature of the oil in a melt pool at 0 to 2°C may attain temperatures of 5 to 10°C (Walker, 1975).

Modelling the evolution of melt ponds has progressed to such an extent that they are now incorporated in climate models (Flocco et al., 2010). Therefore the inclusion of a different albedo for the surface of a melt pond in these models, i.e. that of oil, could be a simple approach in the first instance in understanding the role of oil on the ice surface.

2.6.5 Distance from release point.

The distance from the ice bottom to the depth of the oil release plays an important role in when and where the oil will surface. Lewis, (1975) explains that if an oil droplet of specific gravity 0.8 and diameter 50 microns is released into the sea at 10 m depth, in the absence of any other forces acting upon it, it will take about 5 1/2 hours to reach the surface. If there were a 10 cm/sec current for example, the oil droplet would be carried a distance of 2 km before reaching the ice-water interface. Consequently in the vicinity of a blowout the effects of the released oil could contaminate an area of 2-3 km downstream of the centre of the region, if the disaster were to occur in 60-70 m of water. This effect will be pronounced in regions with strong tidal activity.

2.6.6 Mixed ice/water regions:

In the winter environment the spreading of oil in the open-ocean spreading will typically occur in a lead, and because of the cold temperatures the oil will be more viscous. In summer the typical spreading environment can be anything from fully open water to compact pack. As temperatures will be warmer the oil will tend to be less viscous and spread slightly faster and thinner. The ultimate extent of the spread will of course be dependent on the amount of oil released. Topham (1975) found that minimum equilibrium thickness of the Norman Wells crude on water, under Arctic winter conditions, was approximately 0.25 cm. This equilibrium film thickness is conservative as it is reasonable to assume that this figure will increase as the oil weathers.

As the oil lies on the surface of a lead, it will be "herded" downwind forming a wedge-shaped distribution, with the thickest oil gathering downwind around the ice at the far side of the lead. Increased wave or wind action may allow for oil to be splashed or washed over onto the surface of a floe. Lewis, (1975) suggested that successive opening and closing of the leads, known as lead pumping, could be a significant mechanism in spreading of oil over the ice surface and underside. In winter oil in a lead is susceptible to be incorporated in the newly formed ice. If the lead closes oil incorporated within the new-ice will form the blocks of the pressure ridge, essentially making the oil inaccessible for clean-up operations. A similar process can occur in summer, but rather than new-ice the blocks will be formed from the crushing of the edges of the two floes. Any oil pushed up onto the surface will enhance surface melting in the summer months.

The summer scenario is particularly challenging because the floe concentration within a region is continuously changing with the wind and currents. Floes will come together squeezing the oil between them, or drift apart allowing the oil to spread out over the sea surface. Modelling studies by Venkatesh et al. (1990) suggested that for low sea ice concentrations (less than 30%) oil behaved as in open water, and for ice concentrations higher than 30%, they found that oil drifts with ice. Yapa and Weerasuriya (1997) developed a theoretical model for oil behaviour under drift ice by modifying earlier work on oil under ice to allow for oil escape through cracks. There still remains significant work to be done in this field (DeCola et al., 2006).

2.6.7 Weathering of oil in and on ice

We have seen that crude oil weathers upon exposure to the atmosphere and through this process the more volatile components evaporate, and the remaining oil becomes thicker, more viscous and, less flammable over time. We also know the importance of upper ocean turbulence in the weathering process. However depending on the season and where the oil is located i.e. encapsulated in the ice, below the ice, on top of the ice or on the water the relative importance of each of the seven weathering processes will vary (evaporation, spreading, natural dispersion, emulsification, biodegradation, oxidation and sedimentation). It is an interplay of complex and competing processes and therefore it is extremely challenging to develop accurate modelling to predict the weathering of oil in ice-covered seas over time, because the characteristics of the oil are constantly changing along with the environmental conditions that surround it.

Understanding the weather of oil in the ice-covered seas requires models that can take account of theses complex and varying conditions. A selection of the parameters and variables that influence the weathering process can be seen in table 2.1.

Predicting the weathering of oil in ice-covered waters is presently beyond the capacity of existing models (PEW, 2010), however progress is being made. Recent experimental observations performed in both the field and laboratory clearly showed the importance of understanding the oil properties that have been spilt (Sorstrom et al., 2010). During these experiments five different crude types representing the four different oil types: asphaltenic, naphtenic, waxy, and paraffinic were tested. Tests were performed under a number of different ice conditions, from open water to 90% ice coverage. Results suggest that the asphaltenic and naphtenic oil types demonstrated a rapid and high water uptake, whilst the waxy and paraffinic oil had a reduced water uptake. These results have been used to develop and calibrate a new weathering model that is able to predict the weathering as a function of time. It is now recognized that oil weathering is strongly dependent on the specific chemical composition and characteristics of individual crude oils. (BoHaSA, 2011)

Parameters	Variables
Meteorological parameters	Air temperature, humidity, wind speed, and incoming solar radiation
Oceanographic parameters	Upper ocean turbulence, as well as wave, currents and physical properties, abundance and species of oil-degrading micro-organisms
Sea ice parameters	Ice type (and whether it is growing or melting), ice and snow thickness, ice drift velocity, open-water/lead fraction, under ice roughness
Oil type	Physical oil properties such as viscosity and pour point; chemical properties such as wax content.
Oil spill parameters	Depth of spill (i.e. surface spill or ocean floor release), volume of oil spilt , oil flow rate
Location of the oil	The proportion of the surface area of the oil that is exposed to air (both on the water and on the ice/snow), the amount of oil that is located on under ice or encapsulated within the ice

Table 2.1 showing the parameters and variables that influence the weathering of oil within ice-covered seas.

2.7. Conclusion

There is a wealth of knowledge, expertise and experience in the understanding of oil spills in ice-covered seas that have been gained from over 40 years of research in the field. Nevertheless there are gaps in our understanding, especially in some aspects of the modelling the fate of oil spilled in ice-covered waters. Whilst we have shown that the main mechanisms that govern the fate of an oil slick in the warm open-ocean scenario are similar to those in the ice-covered seas, there are significant and important differences. Many of these processes that govern the weathering and trajectory of oil within an Arctic marine spill are either yet to be parameterised or only crudely represented in models. It is fair to say that on the whole, progress on modelling the fate of oil in ice-covered seas has been slow, and there are many reasons for this; the obvious being the complexity of the system. Like many areas of research these limitations can be overcome. The modelling and observational communities are addressing these challenges through an integrated approach of parameterisations and comparisons with the limited amount of in situ data that is presently available. Results are improving but much work is still left to be done before we can reliably predict overall fate and trajectory of oil spilt in ice–coved waters.

One of the main advantages of numerical simulations is the flexibility it allows in understanding a complex system. However it is easy to fall into the trap of trusting the output of a model without question. And the age old cliché that a model is only as good as the parameterisations and the input data provided remains true. A clear understanding of the limitations of a model is essential.

At present there is a real dearth of *in situ* data for the validation of oil trajectory and fate models. There is a real need for an *in situ* measurement campaign to gather an openly available dataset in order for oil spill modelling teams to validate their model simulations. This benchmark dataset could be used to identify discrepancies between models, enable parameters with a model to be tuned, and allow for new algorithms and parameterisations to be developed as and when needed. Without these data the modelling community is flying blind. Governments, industry, research institutes, and non-governmental organisations have a role to play in ensuring this does indeed happen. A first step along this road is for the modelling and observational communities to identify what set of parameters are most important to measure during an in situ campaign, and at what temporal and spatial resolution.

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3. OIL DETECTION AND MONITORING

by

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Oil detection techniques include those used to determine the spread of oil once a spill is known to have taken place, and those used in routine monitoring. The technologies available have their own specific advanages and limitations as to how they can be applied in the Arctic environment, particularly ice-covered seas. These are reviewed in this report, and affect the reliability in detecting oil, the spatial coverage, and the time taken to deploy and conduct a survey of a spill site. The report is divided into five sections, examining the current state-of-the-art in over, on, in, and below ice oil spill remote sensing. The final section makes recommendations at to future work that should be conducted, particularly concerning the ACCESS experimental tank work in autumn 2012.

Spills of oil in the polar marine environment have a potentially greater environmental impact. This is due to the cold temperatures which reduce the natural dispersion of oil, and the harsh environment which hinders response efforts. There is an increasing risk correlating with increased use of Arctic areas due to retreating sea ice. Both hydrocarbon exploration and extraction activities, and shipping, have increased in the past decade.

The remote sensing of oil spills in sea ice has recently been reviewed by Dickens and Andersen 2009 and Dickens et al 2010, as part of the *Oil in Ice – Joint Industry Programme*. Dickens and Andersen 2009 provides a table, a revised version of which is shown below (Table 3.1), that summarises the applicability of different sensors systems for detecting oil spills in sea ice.

	Ice Surface		**Under Ice**	**Shipborne**		**Airborne**							**Satellite**		
Oil Distribution / Location	*Dogs*	*GPR*	*Sonar with AUV*	*Marine Radar*	*IR*	*GPR*	*Visible*	*ALFS*	*UV*	*IR*	*SLAR*	*MWR*	*SAR*	*Visible*	*IR*
ON ICE															
Exposed on cold ice surface	Y	N/A	N/A	N/A	▒ Y	N/A	■ Y	░ Y	N	▒ Y	N	?	N	■ Y	▒ Y
Exposed on spring melt pools	Y	N/A	N/A	N/A	▒ Y	N/A	■ Y	░ Y	■ ?	▒ Y	?	?	N	■ Y	▒ Y
Buried under snow	Y	Y	N/A	N/A	N/A	Y	N	░ ?	N	N	N	N	N	N	N
UNDER ICE															
Smooth fast ice	?	Y	Y	N/A	N/A	Y	N/A	N/A	N/A	N/A	N	N	N	N/A	N/A
Deformed pack ice	?	?	?	N/A	N/A	?	N/A	N/A	N/A	N/A	N	N	N	N/A	N/A
IN ICE															
Discrete encapsulated layer	?	Y	?	N/A	N/A	Y	N/A	N/A	N/A	N/A	N	N	?	N/A	N/A
Diffuse vertical saturation	?	?	?	N/A	N/A	N	N/A	N/A	N/A	N/A	N	N	?	N/A	N/A
WATER / SLUSH BETWEEN ICE															
1 to 3/10 concentration	N/A	N/A	N/A	?	▒ Y	N/A	■ Y	░ Y	■ Y	▒ Y	?	Y	?	■ Y	▒ Y
4 to 6/10 concentration	N/A	N/A	N/A	N	▒ Y	N/A	■ Y	░ Y	■ ?	▒ Y	?	?	?	■ Y	▒ Y
7 to 9/10 concentration	N/A	N/A	N/A	N	▒ Y	N/A	■ ?	░ ?	■ ?	▒ ?	N	N	N	■ Y	▒ ?
Legend: Y = Likely, ? = Possible, N = Not likely, N/A = Not applicable, ■ = Blocked by darkness, ▒ = Blocked by cloud cover, ░ = Blocked by precipitation (rain/snow)															

Table 3.1: Overview of remote sensing instrument applicability (after Dickens and Andersen 2009).

3.1 Over Ice

3.1.1. Background

Remote sensing of the sea ice surface is routinely done from above the ice. Attempting to detect oil within or under ice presents its own technological challenges which are not easily overcome. The past 20 years has seen major advances in satellite and airborne sensor technologies that allow study of the Earth's surface at a number of radiative frequencies suitable for classifying the type of surface and allowing regular mapping of a number of parameters including, but not limited to, land use, sea ice cover, ocean colour, etcetera.

Whereas in the past there was limited availability of Earth observation data, a number of organisations have promoted free access to satellite data including NASA in the USA, and the European Space Agency (ESA) in Europe. This has made it easier to research into new methods of detecting particular surface types, making algorithms available for the operational community to start producing services covering areas of interest to the community in general. In Europe the Global Monitoring for Environment and Security (GMES) programme, sponsored first by ESA and now taken up by the European Commission (EC), has led to the development of new services.

3.1.2 Satellite Remote Sensing

Spills of oil in the marine environment can have serious biological and economic impacts, and are usually followed by intense public and media scrutiny. Remote sensing from satellites can play a role, both in the 24/7/365 monitoring for unreported spills, and in aiding the response efforts. Whilst remote sensing of sea ice and of the detection of oil spills using satellites are both widely studied, there has been little work to investigate the two in combination. The main problem is how to detect an oil spill if it is from an unknown incident or illegal activity such as discharge. The second issue of how to aid the response effort is more easily solved using standard ice charting and ice management tools.

Both optical and active microwave sensors have been the focus of some preliminary studies on oil spill in sea ice detection. While optical sensors have shown some success in detecting oil spills on top of ice, their use in routine monitoring is limited by the clouds and darkness prevalent in polar regions. Therefore, active microwave in the form of imaging Synthetic Aperture Radar (SAR), is preferred. Although this is proven in detecting oil spills in open water, its use for detecting oil spills in sea ice requires much more work and probably a full investigation of polarimetric SAR techniques using the new generation of satellite sensors that are now becoming routinely available.

A number of review papers are available, including Fingas and Brown 1997, Brekke and Solberg 2005, that describe the available remote sensing technologies for detecting oil spills in open water. These also include in situ and airborne remote sensing techniques, not just satellite sensors. Synthetic Aperture Radar (SAR) is preferred as this provide detection through clouds and darkness. However it is only reliable at moderate wind speeds as the technique relied on contrast in radar energy backscatter between open water and oil contaminated water areas. At low wind speeds, less than 2-3 m/s, there is not enough backscatter from waves on the water for contrast. At high wind speeds, greater than 12-15 m/s, oil spills are broken up and dispersed amongst high backscatter from surface waves.

There have been a great number of studies of the use of satellite remote sensing for monitoring sea ice. These cover the full range of types of sensor available, such as optical and passive or active microwave, both individually and sometimes in combination. Some reviews of the topic are Lubin and Massom, 2006, Massom and Lubin,2006, and Comiso 2009. SAR is also preferred for detailed mapping of sea ice, as performed by the national ice service, as it provides information on sea ice surface features that an analyst can use to evaluate the type and hence thickness of the ice. It is very difficult for a computer to automatically classify open water and ice. This becomes nearly impossible in the summer months when surface melt water reduces contrast for surface features.

The two main uses for satellite remote sensing when dealing with oil spills in sea ice are in initial detection, and once an oil spill has been located, in providing information to help with the tracking of the contaminated ice and aiding the navigation of response teams to the site, so-called ice management. In initial detection, the main question to be answered is how to determine if an oil spill is or has taken place? Oil spills can occur through natural seepages, undetected or unreported accidents, and illegal discharges. Satellites are required to usually required to cover a large area, with a high frequency of observations. However this risks missing small, quickly dissipating, spills.

Ice management is the tracking of the sea ice and oil once the spill location is known. Remote sensing can aid the navigation of response vessels to the spill site. Again a high frequency of observation is desirable. Wide area coverage will provide classification of the regional ice regime. High resolution coverage, with SAR sensors now capable of mapping objects down to a few metres size, can be targeted on the site to provide monitoring of individual ice floes and possible spill mapping.

Synthetic Aperture Radar (SAR)

The state of knowledge regarding the detection of oil spills in sea ice using SAR can be found in a review paper by Tunaley (2010). Radar is the ideal sensor for use in polar regions as it can operate through clouds and darkness. However there is a strong probability of false oil spill alarm due to misinterpretation of look-alike features such as grease ice on open water, the likelihood of radar signals from oil being attenuated by snow or ice, or the radar response to the presence of oil being missed in some manner. The ground resolution of the SAR sensor is important for determining the size of the oil spill that can be detected. Medium resolution SAR, for example those from the European Space Agency (ESA) Envisat Advanced SAR Wide Swath Mode (WSM) or Canadian Radarsat-1 or -2 ScanSAR mode, can provide coverage of very large areas making them ideal for routine monitoring, but the oil spills have to be hundreds of metres in size. High resolution imaging modes, for example the Spotlight modes of Radarsat-2, TerraSAR-X, and Cosmo SkyMed SAR satellites, can provide detection of surface features a few metres across but can only cover very small areas. These are useful for tracking and mapping the extent of a spill that is known to have taken place, and if it remains confined to a small areal extent.

When oil is spilled on Arctic ice it can end up floating on the water between the ice floes, trapped on the ice surface, or enter into the ice through capillary action. Over time and with partial melting, oil may fill pockets within the ice and lie on the surface in pools. Sea ice mapping, such as that done by the Norwegian Ice Service, generally uses medium resolution (100-200 metre) images. These incorporate multi-look processing which averages out speckle noise that can remove small features but makes it easier to see larger areas of differing surface characteristics. A layer of oil on ice has a small effect on SAR backscatter compared to the variations in the ice topography and volume scattering within the ice. Where the oil is within the ice or beneath it, the backscatter from oil will compete with that from brine pockets and natural variations in salinity. Depending on the SAR frequency the incident and scattered signals may be highly attenuated. Therefore backscattered signals from oil may be overcome by speckle in the image or thermal noise in the radar receiver, swamped by natural fluctuations, or severely attenuated by electromagnetic wave attenuation within the ice body.

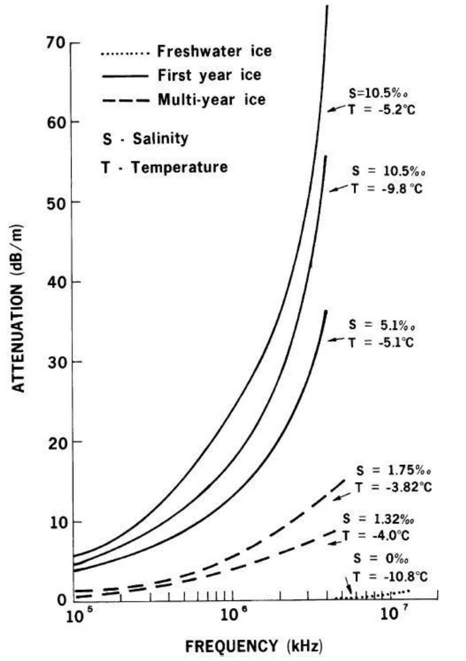


Figure 3.1: SAR signal attenuation (from Fingas and Brown 2000)

SAR signal attenuation depends strongly on the sea ice salinity (Figure 3.1). For C-band (~5 GHz) SAR, as found on the commonly used SAR sensors such as Envisat ASAR or Radarsat, this is around 10 dB/m for multi-year ice, which is less saline, and rises to around 40 dB/m for first-year ice, which still contains many brine pockets. The presence of a backscatter signal for the bottom surface of the ice depends on the change of permittivities at the interfaces, and the bottom roughness. Complex permittivities have been found to be (55.0, -55.0) for sea water, (3.0, -0.4) for sea ice, and (2.0, 0.0) for oil. X-band frequency SAR, such as provided by the TerraSAR-X and COSMO (COnstellation of small Satellites for the Mediterranean basin Observation) SkyMed satellites, is unlikely to be useful due to the very high attenuation. L-band SAR is the most useful frequency for sea ice type discrimination, and probably also for oil spill detection. However this has been unavailable since the failure of the only satellite to carry a sensor with that frequency, the Japanese Advanced Land Observation Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR), in May 2011. A follow-on satellite, ALOS-2 with an improved PALSAR-2, is scheduled to launch in 2013 (Shimada et al, 2011). In addition, the Argentinian component of the Italian-Argentine System of Satellites for Emergency Management (SIASGE) constellation of which the four Italian COSMO SkyMed satellites are part, consisting of two L-band SAR satellites called SAtélite Argentino de Observación COn Microondas (SAOCOM) 1A and 1B, are scheduled for launch at the end of 2014 and 2015 respectively.

There is a need for research to identify a unique feature of oil in sea ice. Typical magnitude images are unlikely to work as the signal tends to penetrate the oil easily at the oil-ice interfaces that might occur when oil pools at the surface, is occluded within the ice, or is trapped on the underside of the ice. The only realistic possibilities for successful detection of oil in ice using SAR involve polarimetric or complex imagery, or a combination of both. As these are only currently available on the very high resolution, limited spatial coverage, imaging modes these can only be used for detailed site surveillance, and not regional monitoring. To maintain wide area coverage but provide most of the polarimetric information, a technique called compact polarimetry is being developed. Unlike fully polarimetric SAR, where the instrument transmits and receives both horizontal and vertical polarisations, compact polarimetric SAR transmits a circular polarization and receives two orthogonal mutually-coherent linear polarisations (Figure 3.2) (Dubois-Fernandez et al, 2008). Compact polarimetry is expected to be available on the future ESA Sentinel-1, from 2013, and the possible Canadian Space Agency (CSA) Radarsat Constellation Mission (RCM), from 2014, C-band SAR constellations.

Fully Polarimetric

$$\begin{bmatrix} 1 \\ \cos\psi_R \cos\chi_R \\ \sin\psi_R \cos\chi_R \\ \sin\chi_R \end{bmatrix} = \begin{bmatrix} \mathit{Kennaugh} \\ 4X4 \end{bmatrix} * \begin{bmatrix} 1 \\ \cos\psi_T \cos\chi_T \\ \sin\psi_T \cos\chi_T \\ \sin\chi_T \end{bmatrix}$$

Compact Mode
CL

$$\begin{bmatrix} \left\langle |E_{RH}|^2 + |E_{RV}|^2 \right\rangle \\ \left\langle |E_{RH}|^2 - |E_{RV}|^2 \right\rangle \\ 2\,\mathrm{Re}\left\langle E_{RH} E_{RV}^* \right\rangle \\ -2\,\mathrm{Im}\left\langle E_{RH} E_{RV}^* \right\rangle \end{bmatrix} = \begin{bmatrix} \mathit{Kennaugh} \\ 4X4 \end{bmatrix} * \begin{bmatrix} 1 \\ 0 \\ 0 \\ -1 \end{bmatrix}$$

[Receive] = [Target] * [Transmit]

Figure 3.2: Components of fully polarimetric SAR and compact polarimetry (from Dubois-Fernandez et al, 2008).

In May 2009 a combination of industry and research partners undertook fieldwork off eastern Svalbard as part of a Joint Industry Program (JIP) project on oil spill contingency for Arctic and ice-covered waters (Babiker et al., 2010). This acquired different types of SAR imagery, including Envisat ASAR, Radarsat-1 and -2, and COSMO SkyMed, to assess oil in ice detection for single- and dual-polarisations. There were no fully polarimetric image acquisitions. Ice conditions were 7-9/10ths concentration with 5-30 metre floe sizes and 15-35 centimetres of snow cover. The study confirmed that the detection of oil in ice-infested waters is hindered by formation of new ice (grease ice) that also dampens waves, and by low speed winds. Rough ice needs to be less than 5/10ths concentration for oil to be detected between floes. The study concluded that small spills contained from spreading within pack ice cannot be detected, and detection is improbable when ice concentrations are moderate to high (greater than 4/10ths). However, as noted above, full or compact polarimetric SAR methods were not evaluated by this study.

Optical

Optical sensors can potentially be used to map oil using its spectral characteristics. However optical sensors are unable to see through the cloud and darkness prevalent in the polar regions. Some sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS) have global synoptic coverage and could be used as the basis for a monitoring service. However these would only detect larger spills. Detailed mapping of smaller spills is possible with multi-spectral high and very high resolution sensors, such as Landsat, Terra ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), IKONOS, Quickbird, DubaiSat-1, and Digital Globe WorldView-2. Although the spectra of oil spills in open water are known, allowing thickness estimation, those from oil in or on sea ice are not.

In April 2003 some oil spills in the Gulf of Finland off of Helsinki allowed the study of optical sensor detection using a high resolution airborne spectrometer (AISA) (Praks et al, 2004). The oil was believed to have come in water discharges from ships that had been beset in sea ice waiting entry into Russian ports. Sample spectra from the airborne sensor were used to determine what the potential responses of satellite sensors including Landsat-7 ETM and MODIS would be. However the oil spill was too small, and was cleaned up by a response team too quickly, to be detected in data from these satellite sensors. Sample optical spectra were determined for 6 classes: clean water, clean ice, clean brash ice, partly contaminated brash ice, partly contaminated ice, and fully contaminated ice (Figure 3.3). It was found that, in comparison to the green visible light band; oil contaminated ice has a high reflectance in the near-infrared (NIR), and that clean open water or ice always has a lower NIR reflectance.

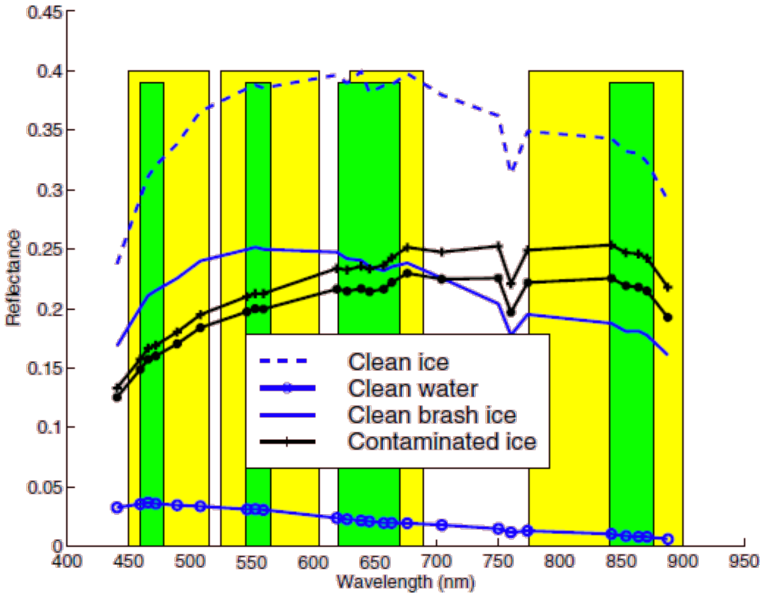


Figure 3.3: Optical spectra for different mixtures of clean and oil contaminate sea ice (from Praks et al 2004).

For detection with MODIS, the green visible channel (4, 545-565 nm) is available at 500 metres resolution. This is not easily used with the high resolution (250 metre) NIR band (2, 841-876 nm). Therefore use of the high resolution red visible band (1, 620-670 nm) was also assessed. This was found to have a slightly reduced, but still usable, detection capability. However when using MODIS oil spills do need to be quite large, of hundreds of metres size, to be detectable.

A second opportunity to assess optical remote sensing of oil spills occurred in March

2006, also in the Gulf of Finland (Wang et al 2008). On the night of 5 March 2006 the Dominican-registered cargo ship, *Runner 4*, collided with a Maltese cargo ship, the *Svjatoi Apostol Andrey*, whilst both were in convoy under the escort of a Russian icebreaker. Damage to the *Runner 4* caused it to sink at 26°19.84'E 59°52.92'N. On board were 102 tonnes of heavy fuel oil, 35 tonnes of light fuel oil, and 600 litres of lubricant oil. These started to appear immediately after the sinking but were very difficult to detect by aircraft during the first week due to heavy ice conditions. Ice at the wreck site was 40-50 centimetres thick, and the oil was either trapped beneath the ice or mixed with broken ice. The oil response operation began when wind created open water areas which allowed the oil to collect. 5 spills were identified in aerial reconnaissance on 15 March of which 4 were 0.01 km^2 and one of 0.09 km^2. These consisted of light and heavy fuel oils and there were two response periods for clearance operations, 15-19 March and 9 April. The overall oil spreading areas was identified to be over 500 km^2.

No analysis of the available satellite data, predominantly MODIS, has been published. For this study the Praks et al 2004 technique was tested on the MODIS images available for the time of the Runner 4 incident. No oil was detected and this failure could be due to the oil type differing from that from which Prak et al 2004 derived their spectra, and the oil being mainly concentrated in small areas along the ice floe edges and hence smaller than the size detectable by MODIS.

Ice Management

Once an oil spill is known, it is possible to use satellite remote sensing to aid the response effort. This is done by managing the ice in the best way possible to ensure a successful clean-up operation. Ice management includes ice charting, to aid the passage of response vessels to the spill site, identification of landing sites for personnel to be landed by aircraft, and tracking of contaminated ice to areas where it can be dealt with in a more suitable way, such as the ice edge when the oil will be released into open water. Response vessels include icebreakers . These should be on standby as part of normal operations and can be used to break the ice into smaller fragments that can be potentially more easily dealt with.

The response to a spill should be to order immediate very high resolution SAR coverage of the affected area. This can be achieved through use of the commercial satellite providers such as Radarsat-2, TerraSAR-X, and COSMO SkyMed. Background monitoring, to determine the regional ice regime, is more likely to be done using medium resolution images from Envisat ASAR and Radarsat-2. The ice drift can be tracked using the different types of satellite image. Forecasts of the ice drift can then be made using ice models driven by available atmospheric and ocean forecasts to determine the likely location the oil will drift to.

3.1.3 Aircraft

Aircraft can carry the same types of sensor as satellites, and their closer proximity to the sea ice surface allows much higher imaging resolutions. Whilst it is easier to target an area using aircraft, they can only cover a smaller area and take a longer time to do so, than satellites. Aircraft remote sensing is a specialised field, with a limited number of aircraft operators. Therefore the available aircraft tend to have a fixed complement of sensors, and adding new ones for specific task requires additional time that may not be available if a quick response is required.

The larger the aircraft, the greater the range, endurance, and different types of sensors that can be carried. Manned aircraft provide the greatest flexibility, but Unmanned Aerial Vehicles (UAVs) are beginning to become more widely available and their ease of deployment, once regulatory hurdles are overcome, may in future make it possible for them to take on more oil spill response work (Mulac et al 2011). Because of the limited sensor payload and endurance of UAVs, but reduced space required for storage, they are suitable for being always on standby at an operations site.

Polar regions can have weather conditions, such as strong winds and icing, that preclude flight operations. Whilst aircraft can fly under typical polar stratus cloud cover, the use of optical sensors is hampered by very low cloud such as frost smoke in very cold conditions, or fog during summer months.

Baschek 2007 provides a review of the different types of available sensor, and how these could be integrated onto a surveillance aircraft (Figure 3.4).

Optical and Active Radar Sensors

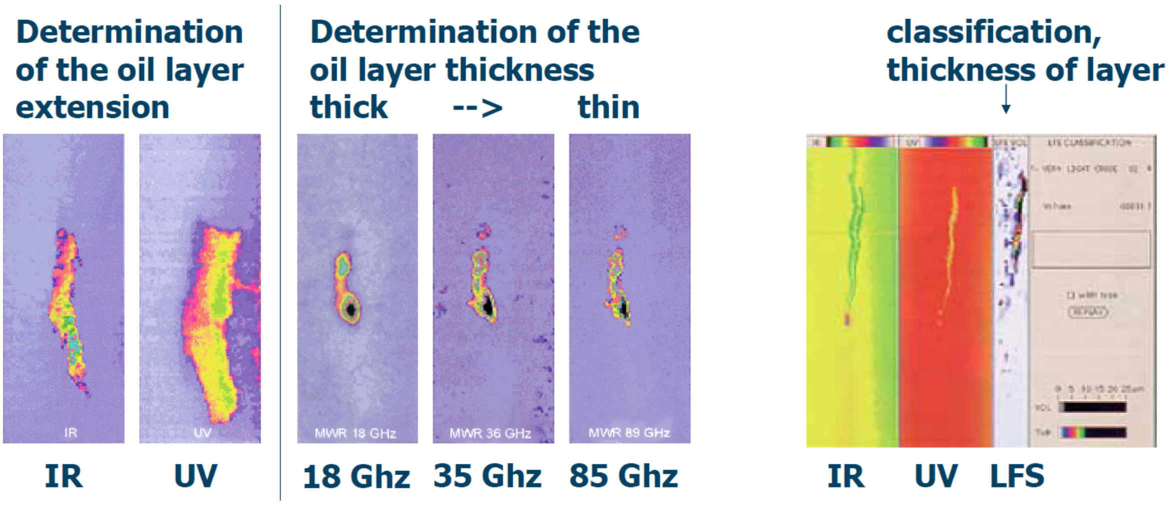


Figure 3.4: Oil spill on open water as seen by different types of airborne sensor (from Baschek 200/).

Airborne sensors such as optical visual/infrared and sideways looking radar (SLAR) are expected to work at least as well in very open drift ice, up to 3/10ths ice cover, as they do in open water. In 4 to 6/10ths ice cover the presence of ice begins to significantly modify slick behaviour by reducing the spreading rate, increasing the equilibrium thickness, and damping wind waves and swell. All of these factors will greatly affect the capabilities and usefulness of different sensors. In close to very close pack ice >6/10, oil slicks are much more likely to remain localized and confined within the ice as discrete thick patches rather than spreading as slicks in the traditional sense.

Ultra Violet (UV) Sensors

Because aircraft, unlike satellites, fly beneath the ozone layer they are able to carry ultra-violet (UV) sensors to measure the sunlight reflected from the surface in the 320-380 nm band. The short wave length of UV has been found to be capable of detecting very thin oil films (> 0.01 µm). However this requires daylight conditions and sufficient visibility.

Passive Microwave

Microwave radiometers (MWR) deployed on aircraft can provide much higher imaging resolutions than their satellite-borne counterparts, and have the advantage of also being able to see through clouds and darkness. Whereas a satellite MWR covers a swath of around 1,500 km with, at best, 6.25 km resolution, an airborne MWR flown at 300 metres has a swath of around 250 metres and a resolution of 5-10 metres.

Oil spills emit a stronger microwave radiation than open water, having an emissivity factor of 0.8 compared to 0.4 for water (O'Neill et al 1983). Lower frequencies provide more robust detection, with lower spatial resolution, with higher frequencies providing more detail at the cost of possible weather related interference. 18.7 GHz allows thickness and volume determination for thicker layers, 36.5 GHz provides good all-weather performance, and 89 GHz high resolution and detection sensitivity to thin layers, Unambiguous detection of thin oil films is in the range of 0.05 to 2.5 mm thickness. Microwave energy emission is greatest when the effective thickness of the oil equals an odd multiple of one quarter of the wavelength of the observed energy. Biogenic materials also interfere and the signal-to-noise ratio is low. In addition, it is difficult to achieve high spatial resolution (Trieschmann et al. 2001).

Laser Fluorometry

Laser fluorometry provide the ability to detect oil spills on water of the range 0.1 to 20 µm thickness. The technique also allows classification of oil types, for example between natural biological oils and mineral oil, and for detection of oil under the water surface. The layer thickness is based on the ratio between the back-scattered Raman signal from, and outside, the oil film (Robbe, 2005). Different oil types are determined through the use of principal component analysis (PCA) of the fluorescence spectra.

Airborne Laser Fluorosensor or ALFS was originally a key element of the *Oil in Ice – JIP* remote sensing project motivated by positive results from earlier tests in Canada looking at oil on the surface mixed with snow and ice in test pans (Dick and Fingas, 1992). However there is a very limited availability of aircraft fitted with this of sensor, or with the open instrument bay capability to carry one, and so it was not possible to test in the field.

Ground Penetrating Radar (GPR)

Initial tests of Ground Penetrating Radar (GPR) have indicated that it is possible to detect oil on top of the ice, but buried beneath snow (Dickens and Anderson 2009, Bradford et al 2010). However the altitude required, around 10 metres, precludes swift aerial surveys of an area and this method is slower than other forms of airborne sensor.

3.1.4 Ships

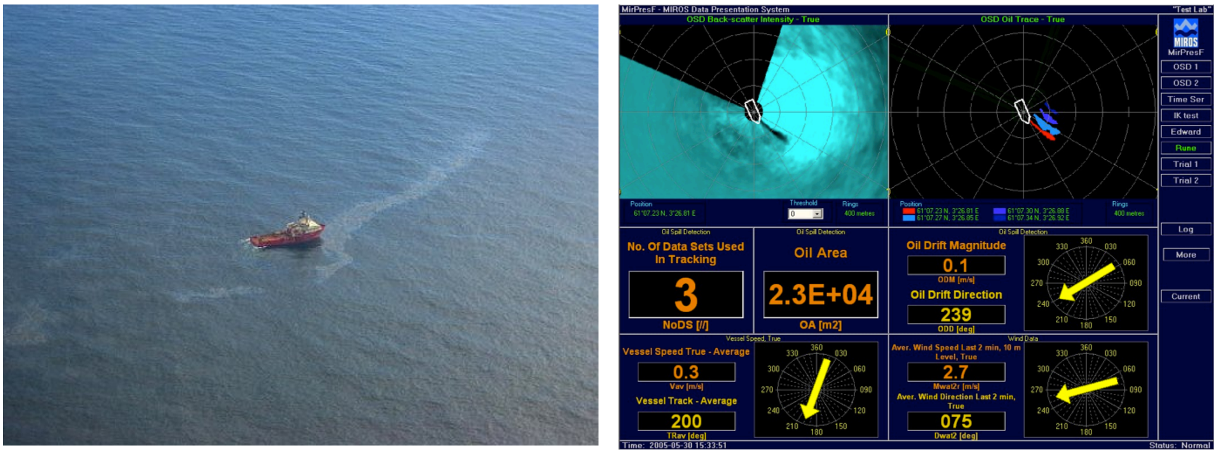
Normally support vessels are on site of operations. However in the event of an incident this may have the safety of personnel as its first priority, rather than oil spill tracking. A ship can be used as base station for airborne, on ice, and underwater oil detection operations and has a greater range than aircraft, but much slower speed. It can also carry and provide power to a wide range of sensors, including all those used on airborne platforms. However unless it is ice capable, the vessel might not be able to follow an underwater plume drifting into an area of heavily concentrated sea ice. The low altitude of masts, relative to ice surface, reduces the spatial area that can be covered as distance objects are viewed at a very oblique angle leading to a foreshortening effect.

Ship Radar

Radar systems installed on ships are typically X-band (8-12 GHz). These are good at detecting ice features such as ice edges and ridges and have been proven in open water oil spill detection. In Norway, the Norwegian Clean Seas Association for Operating Companies (NOFO) has 14 ship-based radar systems, produced by MIROS (http://www.miros.no/), in operation. The radars collect up to 128 scans of a target area and then use processing algorithms for oil detection (Figure 3.5). The range of detection is about 3 km from an antenna height of 18 metres (Dickens and Andersen 2009).

Other systems available include the SeaDarQ system (http://www.seadarq.com/), from The Netherlands, and the Canadian Rutter Sigma S6 ice detection radar (http://www.rutter.ca/).

Whilst shipboard radar systems can detect oil on open water, their use on oil spills within ice-covered waters remains unproven.



MirPresF - MIROS Data Presentation System "Test Lab"

OSD Back-scatter Intensity - True

Position 61°07.23 N, 3°26.81 E

Threshold 0

Rings 400 metres

OSD Oil Trace - True

Position 61°07.23 N, 3°26.81 E; 61°07.27 N, 3°26.85 E; 61°07.30 N, 3°26.88 E; 61°07.34 N, 3°26.92 E

Rings 400 metres

Oil Spill Detection

No. Of Data Sets Used In Tracking: 3 NoDS [/]

Oil Area: 2.3E+04 OA [m2]

Oil Drift Magnitude: 0.1 ODM [m/s]

Oil Drift Direction: 239 ODD [deg]

Vessel Speed, True

Vessel Speed True - Average: 0.3 Vav [m/s]

Vessel Track - Average: 200 TRav [deg]

Wind Data

Aver. Wind Speed Last 2 min, 10 m Level, True: 2.7 Mwat2r [m/s]

Aver. Wind Direction Last 2 min, True: 075 Dwat2 [deg]

Time: 2005-05-30 15:33:51

Status: Normal

Figure 3.5: Oil spill detection by MIROS ship radar system.

3.1.5 Buoys

Buoys do not normally have enough power to carry sensors that can detect oil. However they are very commonly used to monitor ice drift, and so can be deployed at a location where an oil spill has been detected so that the ice can be tracked for subsequent processing by oil spill clean-up teams.

3.2 On Ice

The remote sensing of oil using on or near ice technologies is limited to ground penetrating radar (GPR), and dogs. Very limited area coverage and takes time. Safety aspects of having personnel on ice particularly if in MIZ.

3.2.1 Ground Penetrating Radar (GPR)

Utilisation of ground penetrating radar (GPR) techniques have required advances in information technology and processing algorithms that were not available during earlier oil in sea ice remote sensing studies in the 1970's and 1980's. GPR systems are now commercially available and more portable, allowing their deployment in the field on sledges and from very low altitude aircraft. GPR systems operate in the 500 MHz to 1 GHz frequency range, allowing the radar to possibly penetrate all the way through the sea ice; dependant of ice thickness and the distribution of brine within the ice.

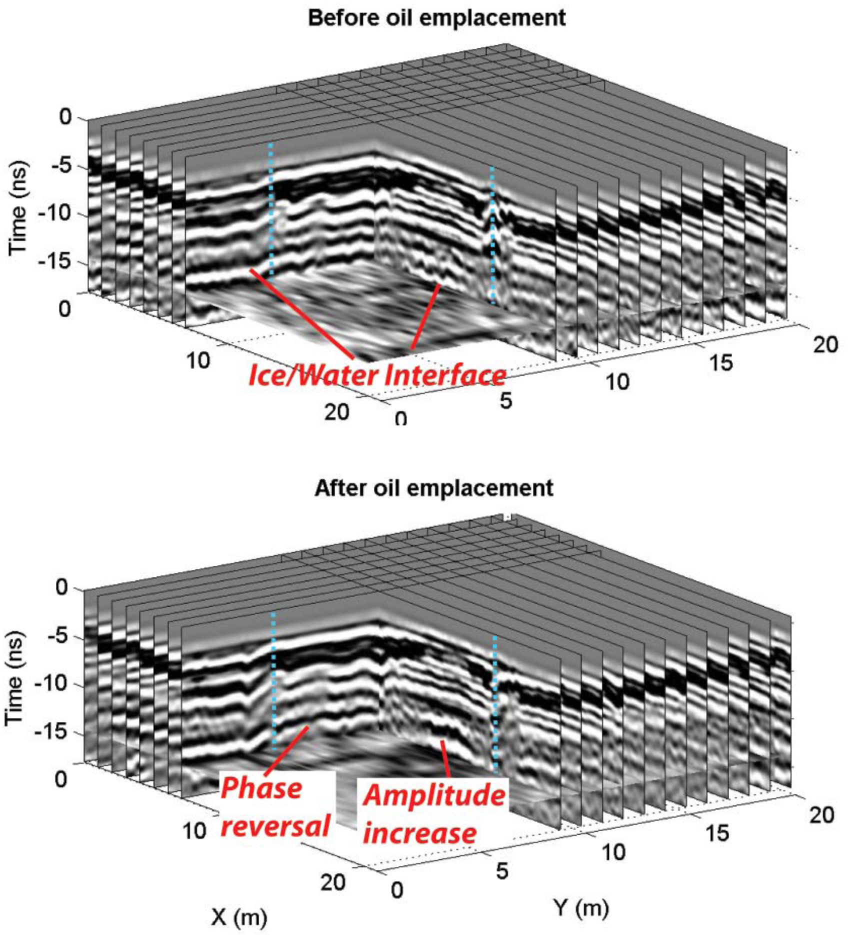


Figure 3.6: GPR images of sea ice before and after oil was placed under the ice (from Bradford et al 2008).

Recent studies have shown that GPR can detect oil layers of about 1-3 centimetres, on ice but buried beneath snow, and trapped in or under relatively smooth ice (Bradford et al 2008, Bradford et al 2010). Although even the best results can be ambiguous, see fig. 3.6. The capacity to detect oil trapped within or underneath ice depends on the ice type. Whilst snow normally has (unless refrozen) a very low electrical conductivity, thus allowing radar propagation, sea ice has a much higher conductivity (> 10-2 S/m) that varies substantially both laterally and vertically (Morey et al., 1984) and can exhibit a high degree of anisotropy due to preferred crystal alignment (Kovacs and Morey, 1978; Nyland, 2004) that affects the ability of GPR to penetrate into the ice and detect oil.. It is more challenging to obtain good GPR surveys from young and first year ice, with its higher proportion of brine pockets.

Processing of data from GPR is computationally intensive. Whilst it is possible to map oil within and under ice using this method, it currently requires extensive post-processing that is not currently available to operators during data acquisition on the ice. An example image (Figure 3.6) from an oil under sea ice experiment shows the typical phase reversal and amplitude increase occurring for oil under ice.

3.2.2 Dogs

A less hi-tec, but more rugged and less prone to failure in harsh Arctic environments, means of detecting oil is provided by specially trained dogs. Sniffer dogs are already used to search out explosives and drugs, and their use for detecting oil buried under snow on sea ice has been field tested as part of the *Oil in Ice – JIP* (Dickens et al. 2010, Brandvik and Buvik, 2009). This study found that the dogs were able to pinpoint the locations of very small oil spills that had been left for a week, determine the dimensions of larger oil spills consisting of clusters of small spills, and indicate the direction to larger spills up to 5 kilometres away upwind.

3.3 In Ice

Detection of oil trapped within ice requires an active sensor system that can penetrate through any overlying snow and ice and obtain a return signal from the oil. The only active sensor system that fits this description is radar; existing sonar systems have too low power to penetrate beyond the water-ice interface. Lower frequency radar systems are better at obtaining signals from within ice, so therefore the typical frequencies of GPR of 500 Hz to 1 GHz, and for SAR L-band (1-2 GHz). As there is limited present availability of L-band SAR systems, the best presently available method for detecting oil within is GPR, as described in the section on on-ice measurements above.

3.4 Below Ice

The detection of oil spills from under the ice is probably the least studied technological sector. This has been due to most oil spill detection studies being concerned with open water and not ice-covered seas, where an underwater approach has not been necessary. Now that the industry focus has moved back towards the Arctic, the use of underwater vehicles whether manned submarines, or unmanned such as Remotely Operated Vehicles (ROVs), operating on the end of tether, and Autonomous Underwater Vehicles (AUVs), would seem to be essential for monitoring oil trapped under ice. All surface remote sensing techniques have problems with detecting oil under the ice cover. This is not so for a system underwater and looking upward. An additional problem has been that, traditionally, under-ice operations have been the preserve of the military. It is only in the past decade or so that technology has advanced to a state where ROVs and AUVs are a practical proposition for under-ice remote sensing (Wilkinson et al 2006). However, most operators of these vehicles are not experienced with under-ice operations.

Unless a nuclear military submarine is available, which is unlikely unless a the oil spill is deemed to be of national significance and the operations cost (~250K GBP per day) is available, then oil spill response is limited to ROVs and AUVs. Both require a ship or personnel on ice to support operations. Generally smaller ROVs and AUVs can be operated by personnel on ice, with larger vehicles requiring support infrastructure such as a ship with heavy lifting equipment. Most underwater vehicles, due to their reliance on battery power or an umbilical tether, suffer from limited range and mission endurance. Refuelling is often slow and requires taking the vehicle out of the water.

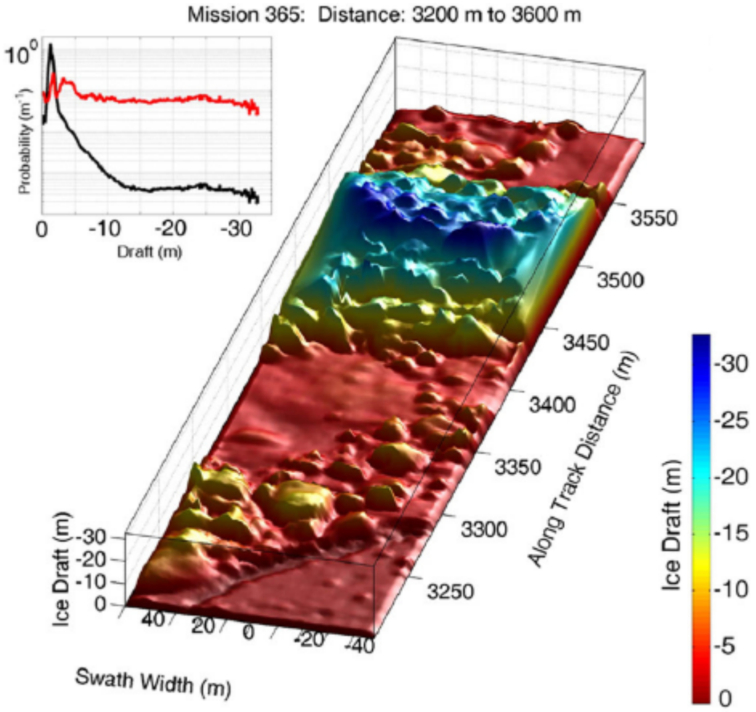


Figure 3.7: Under ice topography as seen by multibeam sonar on an AUV (from Wadhams et al 2006).

The primary remote sensing instrument for underwater use is acoustic, in the form of Upward-Looking Sonar (ULS). This can either be single beam, sidescan, or multibeam. In additional there are water profiling sonars such as the Acoustic Doppler Current Profiler (ADCP). Single and multi-beam sonars are both capable of measuring the thickness of a layer of oil trapped under the ice. Whilst single beam sonar provides a profile of the ice underside along a transect, multibeam is capable of providing a three-dimensional (3D) swath either side of the underwater vehicle track (Figure 3.7) (Wadhams et al 2007). More recently interferometric sonar, providing the benefits of multibeam but the power-saving of sidescan, has been developed (Doble et al 2011). As these technologies are new for use in sea ice studies, there has been little opportunity to test them on experimental oil spills. Latest tests (J.P. Wilkinson, pers. comm. 2012) show that ULS has the ability to penetrate through oil trapped under the ice to the oil-ice interface, offering the capability of mapping under ice topography and oil spill thickness (Figure 3.8). Other standard marine techniques such as upward looking cameras and florescence sensors and others also need their oil detecting capabilities evaluated.

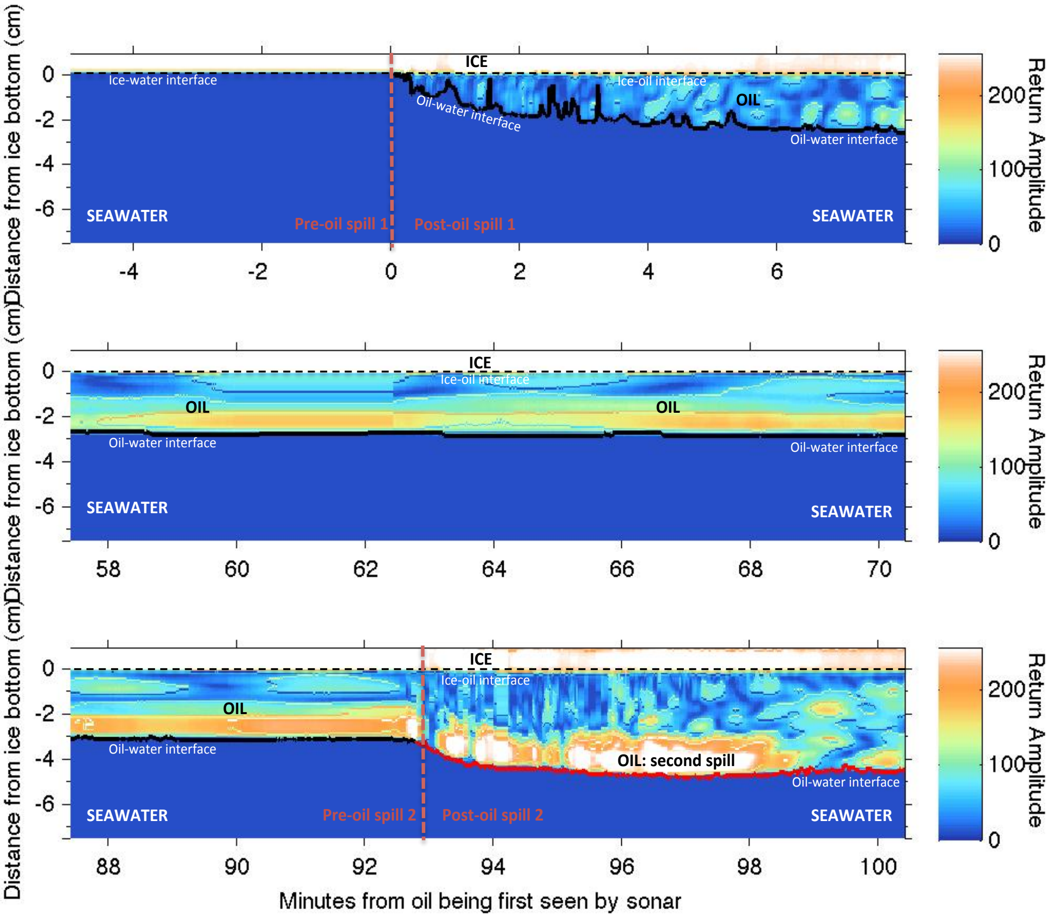


Figure 3.8: Experimental oil spill under ice detected by upward-looking sonar, showing clear detction of oil layer with the ice underside. Time series showing the return amplitude from the upward looking sonar during its deployment under the sea ice and the resultant oil spill. The return amplitude is colour-code with high amplitude returns being white in colour, through to low amplitude returns in deep blue. The black dotted line is the ice bottom, whilst the solid black and red line represent the oil-water interface.

(a: Top) Flowing oil: Time series runs from 5 minutes before to 8 minutes after the oil reaches the region insonified by the sonar

(b: Middle) Immobile oil: Time series runs for 13 minutes and is about one hour after the oil stopped be introduced under the sea ice.

(c: Bottom) Time series runs from 5 minutes before (87 minute mark) to 8 minutes after the second oil spill reaches the region insonified by the sonar (101 minute mark

(J.P. Wilkinson, pers. comm. 2012).

Conclusions and Recommendations

In preparation for the *Oil in Ice - JIP*, the researchers involved made a number of observations (Dickens and Andersen 2009). These are repeated here, with extended interpretation based on this review:

1) There have been few demonstrations of how sensor technologies can detect and map oil under or trapped within deformed sea ice, such as ridges. First year ridges, with void spaces between the ice, pose a problem for remote sensing techniques even without oil. GPR and ULS show potential for mapping oil trapped under relatively smooth sea ice. Of the two technologies, ULS is potentially the most readily interpretable in a field situation.

2) Airborne and satellite-borne sensors for open water applications are expected to work for oil spill detection in very open drift ice, up to 3/10ths concentration. In heavier ice concentrations the sensor performance and limits on detection capability are unknown. IR is likely to work in all ice concentrations, provided the spill is on the surface of the ice (Praks et al 2004).

3) Visible and UV sensors are limited in their practical use in polar regions by cloud and darkness. IR sensors are limed by cloud cover and fog.

4) Airborne and satellite-borne sensors are unable to detect small spills of oils, such as could occur trapped between floes in high ice concentrations greater than 7/10ths, or wind-herded against ice edges. This is due to the sensor resolution.

5) Satellites with very high resolution optical sensors are available, However, although these can resolve features less than 1 metre in size, this is still insufficient to identify small oil pools in heavily deformed sea ice such as rubble fields.

6) The latest generation of SAR satellites (COSMO SkyMed, TerraSAR-X, and Radarsat-2) are capable of resolving targets close to 1 metre in size. However this is at the expense of imaging noise that can hide a feature unless it has a very distinct polarimetric signature. In very open drift ice, less than 4/10ths concentration, these are expected to have similar performance to open water situations. Research needs to be conducted into the polarimetric signatures of oil and ice.

The most practical sensors for immediate oil spill response are those on satellites. These are followed by those on aircraft and from under ice on AUVs, both of which have issues with their availability. Other, on ice, sensors such as GPR and dogs, are applicable but may require more time to deploy and are limited by ice thickness and type.

For satellites the main issue is the lack of test data for oil spills in ice, in particular the fully polarimetric SAR that would provide the best means of classifying different surface types including oil spills. Test spills need to be of a sufficient size to be detectable.

Further work needs to be done to understand the advantages and limitation of the to detect oil and under sea ice from below i.e. from sensors mounted on AUVs and ROVs. Whilst the miniaturised sensor technologies are becoming available, their integration may pose some problems to different classes of underwater vehicles. Further work also needs to be performed in order to evaluate the UAV, AUV and ROV technology itself to understand their limitations and advantages with respect operations under different ice conditions. A similar evaluation should be performed for unmanned aircrafts (UAVs) for the detection of oil from above. These technologies offer the potential of being more readily available, if deployed routinely to operational areas, but at present they are not regularly used within ice-covered seas.

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4. Oil Spill Response Techniques

By

Mark Reed and Alun Lewis SINTEF

4.1 Introduction

The purpose of conducting any oil spill response is to try and reduce the environmental injury that would be caused by the spilled oil if no response was undertaken. The injury that could be caused by the spilled oil may be to ecological resources, or to socio-economic resources, or to both.

The ecological resources at risk from oil spills can include marine species (for example, seabirds, fish, benthos and plankton) and coastal species (for example, inter- and sub-tidal invertebrates, birds such as waders and water fowl) in the affected areas. Spilled oil can cause damage to ecological resources by exerting toxic effects (acute and chronic, lethal and sub-lethal), if the exposure is to sufficiently high concentrations of oil components. The effects of oil pollution can become longer-term if the spilled oil is retained in habitats such as mud-flats or the seabed. Spilled oil can also exert negative effects due to the physical effects of contact with the oil. Seabirds with even small areas of their plumage contaminated with oil can die of hypothermia because the oil reduces the insulating properties of their feathers. Small shallow-water or coastal organisms can be smothered by oil.

The socio-economic, or human-use resources that can be affected by oil pollution include an interruption to fishing in the affected area and possible contamination of the fish caught. If an affected area has industrial or tourist activities these may be interrupted by an oil spill.

The aim of all the limited number of practical oil spill response methods that are available is to prevent or minimise contact of the spilled oil with the resources (ecological or socio-economic) that would be negatively affected.

The appropriateness of any oil spill response technique therefore depends on what is threatened by the spilled oil in the affected area.

4.2 Available oil spill response methods

4.2.1 Monitor and evaluate

In the event of an oil spill at sea it is important that the location of the spilled oil, and how it moves under the effects of wind and currents, is monitored by visual observation from aircraft. This enables the drift of the oil to be tracked and this enables responders to determine what might be affected by the spilled oil and deploy the most appropriate oil spill response methods to the correct locations.

Some remote sensing techniques such as SLAR (Side-Looking Airborne Radar) are useful for locating oil far out to sea. SAR (Synthetic Aperture Radar) images from satellites can also be used to locate spilled oil at sea. UV (Ultra Violet) and IR (Infra-Red) imaging from equipment in aircraft are useful in determining the total extent of an oil slick and the relatively thick and thin oil layers within an oil slick. Multi-spectral scanners of various types have also been used for this purpose.

Monitoring the movement of an oil slick at sea is a passive form of response; the fate and behaviour of the spilled oil is not affected by such surveillance. However, it is an essential pre-requisite for active forms of oil spill response. These techniques and more are covered in chapter 3 .

4.2.2 Mechanical containment and recovery of oil

The purpose of conducting mechanical containment of spilled oil at sea is to limit the spread of spilled oil by containing it within a boom and then recovering the oil from the sea surface and onto vessels. This response strategy will limit the contact of ecological and socio-economic resources with the spilled oil and therefore reduce the damage that would be caused.

Booms are long floating barriers consisting of a flotation chamber from which a 'skirt' hangs into the water. Booms can be used to contain the spilled oil at sea to limit the spread of the oil. The oil can then be corralled into a smaller area to produce a thicker oil layer which can then be removed from the water surface by skimmers, of various types, and transferred into ships for subsequent treatment or disposal on land.

There are various types of booms:

i. Internal foam flotation
ii. Self-inflating
iii. Pressure inflatable
iv. Fence

There are various types of skimmers:

i. Disc/Drum skimmers
ii. Rope skimmers
iii. Sorbent belt skimmers
iv. Submerging plane skimmers
v. Vacuum skimmers
vi. Weir skimmers
vii. Combination skimmers

Each type of boom and each type of skimmer have specific advantages and disadvantages that make them more of less useful in dealing with different types of oil in different spill situations (World Catalogue of Oil Spill Response Products).

The advantage of mechanical containment and recovery is that the spilled oil is removed from the sea surface and is prevented from subsequently drifting to the shore. One of the main disadvantages of mechanical containment and recovery at sea is that it can be slow process; it has a low 'encounter rate' and the oil can spread faster than it can be recovered.

The use of booms at sea is limited by wave height and current speed. Booms are generally not effective with waves greater than 1.2 m high, at wind speeds of greater than 10 knots or with currents (either existing or relative caused by vessel movement) of greater than about 1 knot. This places great limitations on the speed of vessels towing booms to collect spilled oil. Attempting to tow booms faster will cause oil to pass under (or over) the boom and can result in the boom breaking.

4.2.3 The use of oil spill dispersants

The purpose of using dispersants on spilled oil is to transfer the oil from the sea surface and into the water column. This is done to prevent the spilled oil from drifting and eventually contaminating the shoreline.

Technology of dispersant use

Spilled oil at sea disperses naturally (without dispersant addition) to a limited extent. Breaking waves passing through an oil slick convert the surface oil slick, in the localised areas affected by the breaking wave, into oil droplets of various sizes. The largest oil droplets rapidly float back up to the sea surface due to their buoyancy. The re-surfacing large oil droplets will either re-join the oil slick and contribute to the process of water-in-oil emulsification, or will surface in previously 'clean' water and rapidly spread out to form a very thin oil layer, often called 'sheen'. Smaller oil droplets will be retained in the upper layers of the water column by the turbulence (mixing action) that exists there due to wave action. Crude oil droplets with diameters of less than approximately 70 microns diameter have been found to be retained in the upper water column in moderate sea states. For more details see chapter 2.

The active ingredients of oil spill dispersants are the surfactants. When dispersants are sprayed onto the spilled oil on the water surface the surfactants greatly reduce the interfacial tension between the oil and the seawater and this enables the prevailing turbulence of wave action to convert a larger proportion of the spilled oil volume into droplets that are small enough to be retained in the water column. Li et al. (2008) note that two of the most important factors in the effectiveness of a chemical dispersant are the energy dissipation rate which affects the penetration of oil into the bulk aqueous phase and the droplet size distribution of the dispersed oil. Waves can provide a significant source of mixing energy to the dispersion process. Thus the effectiveness of dispersants is derived from a physical-chemical process that includes the chemical properties of the oil and dispersant, and the physical action of the waves (National Research Council, 2005; Li and others, 2008).

Oil spill dispersants, like all other oil spill response methods, have capabilities and limitations. Oil spill dispersants will not cause dispersion of very high viscosity oils and, as the viscosity of oils increases at lower temperature, are likely to be less effective in cold seas than in temperate or tropical seas. The viscosity of a spilled oil increases as the oil 'weathers' (see Chapter 2 of this report) so there is a limited time interval when dispersants will be effective on a particular oil before the dispersant will become ineffective. This is often referred to as the time "window of opportunity" of dispersant use.

Oil spill dispersants can be sprayed from ships or aircraft. Spraying dispersants from large fixed-wing aircraft enables very large areas of spilled oil to be sprayed rapidly. A large aircraft such as the Lockheed Hercules fitted with an ADDS (Aerial Dispersant Delivery

System) pack can spray a total area of 4km^2 in a total spraying time of 20 minutes. However, spilled oil forms slicks where the oil layer thickness varies over a wide range over short distances and accurate targeting of dispersant onto the thicker oil layers is required. Small patches of oil that are more than 1mm thick can exist within a background of 'sheen' that is an average of only 0.1 micron thick. The dispersant spraying systems in aircraft are designed to deposit dispersant at a specified rate over the width of the deposited spray. This is often 5 US gallons/acre (approximately 5ml/m^2) and is based on the assumptions that (i) the oil layer has an average thickness of 0.1 mm, and (ii) the required treatment rate is 1 parts of dispersant to 20 parts of oil (DOR, Dispersant-to-Oil Ratio, of 1:20). Spraying sheen that is 0.1 microns thick with dispersant at 5 US gallons/acre would result in a DOR of 50:1. The sheen would be dispersed, but at 1000 times the theoretically required treatment rate and 99.9% of the dispersant would be wasted. Dispersant spraying should be concentrated on the areas of thicker oil, even if multiple spray runs are required.

Considerations about dispersant use

Dispersants should only be used under circumstances where the prevailing conditions (turbulence, water depth and currents) enable the dispersed oil droplets to be rapidly diluted to low concentrations of oil in water. This requirement is often realised by limiting the use of dispersants to waters of a minimum depth and distance from shore in national regulations.

It is often said that the use of dispersants requires a "trade-off" to be made, because the oil is transferred from the sea surface to the water column. This sometimes misunderstood to mean that the use of dispersants is a "zero sum game" with the transfer of the potential toxic effects of the oil from the 'residents' of sea surface to the 'residents' of the water column, with no overall gain. If this were true, the oil result of using dispersants would be to transfer and not reduce the damage that could be caused by the spilled oil. The often made criticism that dispersants are just being used to hide the oil pollution from sight might then be true.

However, in properly regulated dispersant use this is not the case. While there is an element of 'trade-off' in most decision-making about dispersant use particularly in shallow water, there can, in many circumstances, be a very marked advantage in using dispersants. If a particularly sensitive coastal resource such as a mud-flat or salt-marsh is likely to be contaminated by the spilled oil if it drifts ashore, the decision to disperse the oil while it is still in deep water may cause only minimal and transient effects on marine life. It has been found from past practical experience (*Sea Empress* and *Braer* incidents) that the temporary elevation of dispersed oil concentration in the water causes only localized and transient negative effects to some marine species. The benefits of dispersing the oil at sea will be the prevention of much greater and longer lasting damage to the coastal habitats and the various species that reside in those habitats.

The assessment of the potential benefits and risks of using dispersants on spilled oil is referred to as NEBA (Net Environmental Benefit Analysis). The principle of NEBA is that any response option should produce the "least-worse" outcome of an oil spill by considering the overall amount of damage that could be caused to all resources and not concentrating on one aspect (for example, the seabirds or the fish) to the exclusion of the others. The use of

NEBA should enable a demonstrable benefit from using dispersants on the oil to be made on a case by case basis.

4.2.4 In-situ burning

The purpose of in-situ burning of spilled oil at sea is to remove it from the sea surface. This response strategy will limit the contact of ecological and socio-economic resources with the spilled oil and prevent the oil from drifting ashore.

Oil spilled onto the sea rapidly loses the more volatile (and flammable) components by evaporation into the air. This makes the oil progressively more difficult to ignite. Spilled oil rapidly spreads out to form very thin layers and these will not sustain combustion due to heat loss to the underlying water. In order to burn oil at sea it must first be collected in booms and the thickness of the oil layer be increased to at least 2 or 3mm. The minimum oil thickness for successful burning increase as the oil weathers and highly emulsified oil cannot be ignited. The limitations of collecting spilled oil into booms imposed by wave heights, wind speed and current speed have already been described in Section 4.2.2. The oil will then burn if an ignition source is applied, plus some fuel such as gelled petrol (gasoline) is added. The boom used to contain the oil must obviously be fireproof if the oil is to be burned.

One of the key challenges to the effectiveness of ISB is maintaining sufficient thickness of oil to sustain a burn. The minimum ignitable thickness of a fresh crude oil slick on water is about 1 mm, whereas for aged, unemulsified crude oil the minimum thickness is on the order of 2–5 mm (Potter and Buist, 2008). Emulsification is an important process affecting the effectiveness or the response window of opportunity for use of ISB, because the oil in the emulsion is not able to reach a temperature to burn until the water is first boiled off (Potter and Buist, 2008). Emissions from ISB include the release to the atmosphere as well as burn residue. The residue from an ISB may float on water or sink, depending on the oil type and the extent of the burn.

Burning oil at sea generates copious amounts of smoke because the basic layout of a pool-fire restricts the access of air to the base of the flame. Moderate wind speeds help combustion. Not all the oil will burn and a viscous, high-density tarry residue, perhaps 5% of the original volume of the oil, will remain. This residue can rapidly pick up sediment from the water and then it will sink to the seabed.

4.2.5 Protective shoreline booming

The purpose of deploying booms near shoreline resources that could be impacted by spilled oil is to prevent contact of the resource with the oil. The use of active, at-sea responses such as mechanical containment and recovery, the use of dispersants and/or in-situ burning is unlikely to be able to prevent 100% of the oil drifting to shore. Some spilled oil is likely to eventually drift ashore and surveillance from aircraft (Section 4.2.1) should be used to track the drifting oil so that booms can be deployed in the appropriate locations.

4.2.6 Other oil spill response techniques

Since the *Torrey Canyon* oil spill in 1967 a lot of ingenuity has been expended to try and develop new or novel oil spill response methods and to improve the performance of the existing oil spill response methods described above. Various novel techniques have been considered, including:

- Solidifiers to convert spilled oil from a liquid state into a solid state by the addition of various polymers.
- "Herding agents" that are sprayed around the spilled oil and act as chemical booms to contain spreading spilled oil.
- Surface cleaners to remove oil from hard surfaces.
- Fertilisers (nutrient blends) or microorganisms that have been cultured to accelerate the biodegradation of spilled oil.

4.3 Purpose of oil spill response in ice-covered waters

In common with oil spill response in open-sea, temperate conditions the purpose of conducting any oil spill response to oil spills in ice-covered waters should be to reduce the damage that the spilled oil might cause. It is therefore necessary to know which resources, both ecological and socio-economic, are likely to be damaged by the spilled oil at a particular location so that the appropriate response strategy and methods can be used to minimise the damage that could occur.

4.3.1 Ecology of ice-covered waters

The ecosystems in and around waters that may be ice-covered are highly dynamic and very seasonal. The ecology of seas that might have periodic ice cover is governed by many factors and ice cover is only one of several factors. It is not possible to consider a generic ecology of ice-covered waters. The Arctic and Antarctic regions of sea are both dominated by generally low temperatures, the presence of ice and long periods of continuous darkness in the winter and a brief summer of continuous daylight. However, the ecology of these two regions is different for other reasons. The Arctic Ocean is surrounded by landmasses with only two relatively narrow, shallow connections to the Atlantic (Fram Strait) and the Pacific (Bering Strait). There are also many river inputs. In contrast, the Antarctic is surrounded by oceans with open access, has a central landmass and there is no river input. The ice conditions in the two regions are different; the Arctic has much more ice cover in summer in winter and thicker, multi-year ice. The Antarctic is far richer in species of the benthic organisms and has a higher diversity than the Arctic.

A comprehensive description of the ecology of ice-covered waters is outside the scope of this report, but the following brief overview is given to indicate some of the ecological resources that would need to be taken into account in any oil spill contingency planning.

Primary and secondary productivity

The level of primary production in the Arctic is generally low and strictly seasonal, limited to a short period of a few months in ice-covered waters of the high Arctic. A large number of planktonic algae thrive in Arctic waters. In addition, ice algae growing on the under-surface and in crevices of the ice contribute to the plant production in the marine Arctic. Little light penetrates thick sea-ice and most production of phytoplankton takes place when the ice melts. In the winter there is no light available for photosynthesis and the mixing of the upper water column to supply nutrients is greatly reduced when total ice cover is present. Secondary producers include the microbes and zooplankton that consume phytoplankton and algae. The dominant herbivores among the zooplankton are relatively large (4 to 8mm long) copepods that have sufficient mass to survive a long winter period without feeding.

Benthos

Benthic food supply originates in surface waters and is highly seasonal in the Arctic. The shallow coastal waters support considerable and diverse bottom fauna of crustacea, molluscs, sponges, worms, anemones and starfish with various small fish. They graze the algae or feed on detritus or plankton and provide a food source for larger fish, birds and mammals such as walrus and seals. The shallow waters are also the spawning ground for capelin, polar cod and other fish in March and April.

Marine Fish

Marine fish in Arctic waters include:

- Fish at or near the seafloor of the continental shelf such as polar eelpout, and Arctic flounder;
- Fish within the water column of the continental shelf such as Pacific herring, Arctic cod, capelin, and Pacific sand lance;
- Fish living on or close to the bottom off the continental shelf such as ogac, ribbed sculpin, spatulate sculpin, shorthorn sculpin, spinyhook sculpin, archer eelpout, pale eelpout, and daubed shanny;
- Fish inhabiting the deeper water column of oceanic waters such as Pacific herring, Arctic cod, polar cod, pollock, Pacific sand lance, and the glacier lanternfish; and
- Fish inhabiting oceanic waters, but during their lifecycle, are associated with sea ice such as Arctic cod and Pacific sand lance.

Marine Mammals

The marine mammals found in the Arctic include baleen and toothed whales (Bowhead Whale, Gray Whale and Beluga Whale), ice seals (Ribbon Seal, Ringed Seal, Bearded Seal and Spotted Seal), walruses, and polar bears. Seals and whales have an insulating layer of blubber to reduce heat loss. Being warm-blooded, they need to metabolize food to generate heat to survive. They draw upon the stored lipids as an energy store for this purpose during winter, while their large body size at the same time allows them to survive long periods without food. As the apex predator in the Arctic marine ecosystem, polar bears specialize in living off stored lipids obtained from their primary prey the ringed seal and bearded seal.

Marine and Coastal Birds

Each spring and summer, large numbers of animals arrive as visitors to feed and grow during the short Arctic summer. This includes shorebirds and waterfowl, such as geese and ducks that use the Arctic as their breeding area. Arctic resident species may move between high Arctic summer areas and low or sub-arctic winter areas. There are about 200 species of Arctic birds; about 70 species of seabird, 60 of waterfowl and about 70 shorebird species. Most of them are temperate species with breeding ranges extending into the sub-arctic zone. Many shorebirds and waterfowl such as ducks are mainly inland species associated with freshwater wetlands. Many seabirds (e.g. skuas or jaegers) and most waterfowl and shorebirds breed inland on tundra and wetlands, but most of them move to coastal and marine habitats after breeding. In the summer, on the mudflats and sandy shores, vast numbers of waders feed on small crustaceans, molluscs, worms and small fish. Waders (dunlin, knot, sandpipers and stints) breed almost exclusively in the Arctic with total populations of individual species of up to 3.5 million birds. Very large colonies of guillemots (murres), auks, gannets, cormorants and puffins can be present at some locations. The majority of species are migratory to lower northern latitudes or the southern hemisphere. Some species are more true Arctic residents and move to winter mainly in the sub-arctic zone.

4.3.2 Socio-economic use of ice-covered waters

The Arctic is inhabited by several different groups of indigenous people, and also by relatively recent immigrants of mostly European background. The prevailing conditions dictate the lifestyle to a very great extent. While temperatures are below freezing, the frozen, snow covered ground, ice-covered rivers, and shore-fast ice are utilized for transportation using dog sleds (traditionally) or snowmobiles (recently). In warmer weather, transportation is based on small boats on ice-free coastal waters and flowing rivers. Most indigenous people live along the coast or on river banks. Generally, subsistence is considered hunting, fishing, and gathering for the primary purpose of acquiring traditional food. Diet is based on foods that can be taken from the natural environment (fish, seals, whales, caribou, birds, berries, plants), since agriculture is impossible. Subsistence harvests are seasonally and regionally variable. Recent discoveries of oil, minerals, and diamonds in Arctic areas, and a growing interest in Arctic tourism are bringing many non-indigenous people to the Arctic to live or visit. Simultaneously, the indigenous people are blending many parts of western civilization into their lifestyle.

Oil spill contingency planning for locations in ice-covered waters

Considerations of the likelihood of oil spills occurring, the probable consequences for the ecological and socio-economic resources within the affected area and the feasibility of using oil spill response methods to minimise the damage that could be caused by spilled oil are best undertaken in oil spill contingency plans. These plans should be prepared for specific activities, such as oil exploration/production or shipping corridors, at particular locations.

In view of the very seasonal fluctuations of the conditions, including the presence of ice, but also including the low temperatures and periods of darkness and light, plus the highly seasonal fluctuations in the ecological and socio-economic resources that may be present, any oil spill contingency plan for ice-covered waters will need to consider the seasons.

Detailed data will need to be gathered on the species that are present in the area and how these populations change with the season.

4.4 Methods of oil spill response in ice-covered waters

There have been many research programmes into methods of oil spill response in ice-covered waters including containment and mechanical recovery, burning, bioremediation, and enhanced dispersion. Recent reviews and investigations include:

- Advancing oil-spill response in ice-covered waters: Report prepared for the Prince William Sound Oil Spill Recovery Institute and the U.S. Arctic Research Commission (D.F. Dickins Associates, Ltd., 2004)
- Arctic oil spill response research and development program — A decade of achievement: (Minerals Management Service, 2008)
- SINTEF Joint Industry Program (JIP): Oil in Ice Program (SINTEF, 2010)
  - Joint industry program on oil spill contingency for Arctic and ice-covered waters—Summary report: SINTEF Materials and Chemistry, Oil in Ice – JIP Report, no. 32, (Sørstrøm et al, 2010) and other reports, available at http://www.sintef.no/project/JIP_Oil_In_Ice/Dokumenter/publications/JIP-rep-no-32-Summary-report.pdf.
- An evaluation of the science needs to inform decisions on Outer Continental Shelf energy development in the Chukchi and Beaufort Seas, Alaska: U.S. Geological Survey Circular (Holland-Bartels, Leslie, and Pierce, Brenda, eds., 2011)

The oil spill response methods that would be feasible or effective for spills of oil in ice-covered waters vary depending on the seasonal ice and other conditions. The behaviour of oil spilled in cold, ice-covered waters is governed largely by the ice concentrations in the case of broken ice and the process of encapsulation and subsequent migration in the case of solid ice (see Section ?.?.?).

If oil was spilled under ice in the spring (after May), the oil might not become encapsulated in the ice due to insufficient new ice growth before seasonal melting commenced (Buist and others, 2008a). Conversely, a spill occurring just prior to or during freeze-up (Lewis and others, 2008) may become rapidly incorporated in ice, such that response efforts could include a combination of oil recovery and ice tracking and monitoring operations.

Each season presents different advantages and drawbacks for spill response:

- During the summer open-water season, oil spill response will be as it is any temperate sea.

- During freeze-up and ice growth, drifting ice and limited site access will restrict the possible response options.
- Mid-winter, with long periods of darkness and intense cold, provides a stable ice cover that not only naturally contains the oil within a relatively small area but fast-ice also provides a safe working platform for oil recovery and transport.
- During the thaw, break-up and finally melt of the ice
- Response to oil spills in moving pack ice are likely to be more limited.

4.4.1 Mechanical containment and recovery of oil in ice-covered waters

Mechanical recovery has been demonstrated to be a practical strategy in solid, fast ice (Allen and Nelson, 1981; Alaska Clean Seas 1999).

Booms

It is obviously not feasible to use a floating boom to contain spilled oil if there is total ice coverage or encapsulated within the ice itself. The oil will either be on top of the ice, possibly covered by snow, on the underside of the ice. Partial ice cover will act a series of naturally occurring booms, limiting the spread of the ice in certain areas. Sea ice coverage greater than about 60 percent, the ice itself can potentially serve as a natural containment barrier (Dickins and Buist, 1999).

When responding to an oil spill in Arctic conditions, the first step is to identify the oil's physical properties particularly the Pour Point. If the Pour Point is 5ºC to 10ºC degrees above the water temperature, there is a strong possibility that the oil will be solid. Nets and other collection devices may be required for recovery. If the Pour Point of the oil is below the water temperature and if currents and wind conditions allow, then booms and skimmers may be applicable for use.

The basic problem about using booms to contain spilled oil in partially ice-covered waters is that the boom contains floating ice as well as floating oil. The feasibility of using booms is therefore related to ice coverage. Ice concentrations as low as 1/10 ice coverage or less negatively affect large, open towed-boom systems. Attempts to tow a boom from a vessel to contain spilled oil will result in a lot of ice being 'captured' within the boom. This will put a strain on the boom, tear the flotation chambers and possibly break the cables within the booms.

Conventional booms will quickly collect ice and subsequently lose oil as the flotation chambers are submerged or lifted out of the water. There are a number of types of booms available for use low coverage concentrations of ice in ice-covered waters (DeCola et al., 2006). Ice booms also have the capability to assist other mechanical recovery systems by providing an ice-free environment, and in separating oil from ice (Abdelnour and Comfort, 2001; Abdelnour et al., 2001). The collection of spilled oil in booms is feasible, with suitable techniques and reduced effectiveness, up to 3/10 ice coverage. Available estimates from mechanical response in broken ice vary from 1% to 20% depending on the degree of ice coverage and if responding during freeze-up or spring break-up. This compares with estimates of 5 to 30% for open ocean response without broken ice.

Recent advances in technology have been made to extend the capability of ice booms, adapting technology that had been in use for several decades to protect water intakes upstream of hydroelectric power plants into a countermeasure for oil-spill response. Techniques to deflect and separate oil from ice on the sea surface, such as using prop wash or pneumatic bubblers, may enable mechanical systems to encounter and recover oil at higher rates in the presence of drifting ice.

Skimmers

The most appropriate skimmers for ice-covered waters are the oleophilic rope mop and brush skimmers. These skimmer types are preferred because other skimmers will quickly become clogged with smaller pieces of ice. Even very low concentrations of ice seriously affect the performance of most skimmer systems through plugging and bridging. Skimmers work best when positioned in open water and in leads between ice pieces.

Two programmes that have developed mechanical oil recovery systems for deployment in ice-infested waters are (i) the Mechanical Oil Recovery in Ice-Infested Waters (MORICE) project (Jensen and Mullin, 2003) and (ii) the Lamor Oil Ice Separator (LOIS) (Minerals Management Service, 2008). The LOIS is a commercially available mechanical recovery system consisting of an oscillating ice grid that washes oil from ice chunks as they move along a grid; the oil is subsequently concentrated for recovery by a skimmer.

Solsberg (2008) noted that there have been several recent advances in mechanical recovery systems for spill response in Beaufort Sea spring breakup or fall-freeze-up seasons,. However, there can still be severe limitations during deployment due to ice-processing challenges, extreme weather (freezing) conditions, and changing conditions in the ice itself. Nuka Research and Planning Group, LLC (2007) points out that the range of ice conditions that may be encountered in the Beaufort Sea is an important factor when determining what types of technologies are “appropriate and reliable” for oil-spill response and recovery.

4.4.2 The use of oil spill dispersants in ice-covered waters

The use of dispersants on spilled oil at sea requires substantial logistic support. Stocks of dispersant must be available for immediate use and further supplies will be required if the amount of oil spilled, and the amount of dispersant required, is large. Specialist dispersant-spraying equipment, mounted on surface vessels or aircraft must also be available, together with crews trained to use it. Dispersant-spraying aircraft require runways of suitable length, supplies of fuel and maintenance facilities. It can be difficult to mount a dispersant-spraying campaign if the equipment has to come from far away and can be difficult to maintain it without sufficient support. All of these issues will be made more difficult if oil is spilled into an ice-covered sea in a remote region.

The use of dispersants in a conventional way; by spraying dispersant onto large areas of spilled oil on the sea from surface vessels or aircraft will be limited by ice coverage. Dispersant sprayed over a large area will be deposited on the spilled oil between broken ice pieces, but also on the broken ice. As the spilled oil will be concentrated on the sea surface between the pieces of broken ice, it will be in layers that are thicker than if the ice was not there. A thicker layer of oil requires more dispersant to be deposited onto it to achieve the recommended dispersant treatment rate.

The technical challenges of using dispersants on spilled oil on an ice-covered sea can be summarised as:

I. Delivering the required amount of dispersant to the spilled oil.

II. Ensuring that there is sufficient agitation to cause initial dispersion of the oil as a plume of very small oil droplets. This mixing energy is normally provided by breaking wave action in the open sea, but this will be limited in the presence of ice.

III. Ensuring that there is sufficient dilution potential so that initially dispersed oil is diluted into the upper layers of the water column. This dilution is also normally supplied by wave action in the open sea, but will also be limited in the presence of ice.

Dispersants can be effective in broken ice provided there is some mixing energy available, and wave reflection among broken and brash ice may serve as highly localized sources of mixing energy (Minerals Management Service, 2008). Given this potential source of mixing energy, there also is a need to characterize specific energy distributions on a more localized scale, that is, at the point of dispersant application, such as energy added from the ship’s propellers or via high-pressure water systems to enhance mixing (Sørstrøm et al., 2010). A recent study by Nedwed et al. (2007) tested the potential for an azimuthal stern drive (ASD) from an icebreaker as a means to provide the mixing energy necessary to disperse chemically treated oil slicks in broken ice. There has been recent work to develop new formulations of dispersants (Nedwed et al., 2008) that can be applied to an oil slick as a gel, and thus potentially be more effective on oils with higher viscosities.

Brandvik et al. (2006) report that dispersants can be a suitable oil spill response in Arctic waters in open water and up to 50-percent ice-covered. In a recent review of dispersant effectiveness under Arctic conditions, Lewis and Daling (2007) identify that factors such as salinity of sea ice and colder temperatures affect the viscosity of spilled oil and may reduce the effectiveness of dispersant applications. These conditions also inhibit oil weathering factors, such as the formation of emulsions (Fingas, 2008b). Thus, the window of opportunity during which dispersants may be effective may be extended.

Laboratory studies by Moles et al. (2002) found that at the conditions typical of Alaskan estuaries and marine waters, dispersant effectiveness was at study detection limits (less than 10 percent). Some dispersants are more sensitive to salinity and temperature, and measured effectiveness can vary by roughly a factor of 10 or more (Lewis and Daling, 2007).

However, results from tests conducted at the National Oil Spill Response Research and Renewable Energy Test Facility (formerly OHMSETT) using four Alaskan North Slope crude oils and two dispersants found that the dispersants were more than 90 percent effective at dispersing fresh and weathered forms of the oils under cold weather conditions (Mullin et al., 2008; Belore et al., 2009).

Ecological considerations for dispersant use in ice-covered waters

Dispersing spilled oil into the open sea by the use of dispersants will convert a much greater proportion of the oil volume into oil droplets that are small enough to be retained in the water column by the prevailing turbulence, than is the case for natural dispersion (dispersion of oil by only breaking wave action). In the case of natural dispersion, the oil droplets that are too large to be retained in the water column will be the greater proportion of the affected oil and these droplets will float back to the sea surface. In the case of dispersant use, the proportion of oil converted into droplets that are small enough to be retained in the water column by the prevailing turbulence will be much greater than in the case of natural dispersion, but is still unlikely to be 100% of the affected oil; some proportion of the oil volume will resurface. This resurfacing oil will either re-join the original oil slick or surface in 'clean' water where the droplets rapidly spread out to form sheen.

The ecological concerns expressed about dispersant use in open water normally involve:

i. The increased exposure of some marine organisms to the partially water-soluble compounds from the oil that are more easily liberated when the oil is dispersed into small oil droplets, by virtue of the increased oil / water interfacial area, and

ii. The increased exposure of some marine organisms to the higher molecular weight PAHs (Polycyclic Aromatic Hydrocarbons) that are not water soluble and stay with the oil droplets, but which can be ingested by some organisms because of the similarity in size of dispersed oil droplets to plankton. This can concentrate the PAHs from the oil within some organisms. This may, or may not harm these organisms, but they are the prey of higher-level species and the potential for harm may be passed on up the food web.

Dispersing oil into ice-covered waters presents somewhat different considerations to dispersion of oil in the open sea.

The level of turbulence in the upper water column will be lower under ice than in the open sea and the size of oil droplets that will be retained will be smaller than that in the open ocean. Localised intense mixing of dispersant-treated oil by the use of ship's propellers or other means will cause all of the oil to be initially dispersed into the water column. The smaller droplets will be retained in the water column by whatever turbulence prevails, but some proportion of the droplets will be too large to be permanently dispersed. These oil droplets will float towards the sea surface. If these oil droplets eventually resurface under ice they will be trapped there. The oil droplets would then be in close contact with ice algae.

The pre-existing ecological concerns about the effects of dispersed oil on marine organisms could need to be supplemented by concerns about the potential effects of temporarily dispersed oil.

There is uncertainty regarding the effects of dispersants on marine organisms in the Arctic (World Wildlife Fund, 2009). One of the uncertainties is the potential effect of dispersants on the natural processes of microbial degradation of oil and how this may affect the toxicity of the residual oil.

4.4.3 In-situ burning in ice-covered waters

Some of the earliest in-situ burning activities were laboratory, tank, and field studies conducted in the 1970s associated with drilling in the Canadian Beaufort Sea (Potter and Buist, 2008). A series of successful Arctic field experiments in the 1970s and early '80s was largely responsible for helping in-situ burning become accepted as the most effective oil recovery strategy in situations involving spills in ice-covered waters.

Research and development efforts intensified in the years following the Exxon Valdez spill in 1989 to improve fire-resistant boom design, refine operational procedures and to resolve issues associated with air pollution from burning. These research efforts culminated in an international, multi-agency research burn in August 1993, offshore St. Johns, Newfoundland known as the Newfoundland Offshore Burn Experiment or NOBE (Fingas et al. 1995) The experiment verified that in situ burn operations can be conducted safely and effectively with burn efficiencies exceeding 90%, addressed many of the uncertainties regarding air contamination and confirmed the overall viability of in-situ burning as a legitimate response countermeasure.

Oil may be more difficult to ignite at low temperatures but once burning begins, it will continue regardless of ambient temperature. The effectiveness of in-situ burning can be affected by weather and sea-state conditions, but ice coverage is also a very important factor. At ice coverage exceeding 70 percent, in-situ burning can be conducted without any mechanical containment systems, as the ice provides a natural barrier to restrict the movement of oil across the water surface. At ice concentrations less than 30 percent, open-water in-situ burning may be feasible (Brandvik et al., 2006; Potter and Buist, 2008), including the use of oil containment with a fire-resistant boom.

Ice concentrations of 3/10 – 7/10 percent are considered to be the "most difficult from an *in-situ* burning perspective" (Juurmaa, 2006). These ice concentrations are high enough to impede the effectiveness of mechanical containment systems, but too low to serve as a natural containment barrier for the oil (Brandvik et al., 2006; Potter and Buist, 2008). In addition to the ice coverage, the type of ice present can alter the effectiveness of in-situ burning (S.L. Ross Environmental Research, Ltd., et al. 1998). Conducting in-situ burning in pack ice during break-up may be more effective at removing spilled oil than when there is a similar amount of ice coverage during the fall freeze-up, because the fall freeze-up generates significant amounts of slush ice that can impede containment of slicks (Potter and Buist, 2008). Brandvik et al. (2010) report in-situ burning efficiencies ranging from 50 to 90 percent in field tests (during about 7/10 – 9/10 ice coverage) and meso-scale laboratory experiments in a wave tank under varying ice coverage conditions (no ice, 5/10 and 9/10 ice coverage). In field and the meso-scale trials at 9/10 ice coverage, in-situ burning had a long window of opportunity, about 120 and about 140 hours, respectively. Meso-scale experiments with no ice present had less than a 5-hour window of opportunity and only slightly better, about 10 hours, at 5/10 ice coverage.

In-situ burning can be the preferred response strategy for oil spills in broken ice where it is not safe to work in or on the ice. In-situ burning can also be the preferred technique for dealing with spills on ice and snow-covered surfaces; oiled snow with as much as 70% snow by weight can be burned. In-situ burning is also a possibility for oil released through brine channels into melt pools in the ice during spring thaw.

4.4.4 Chemical herders used in conjunction with in-situ burning

Chemical herders, sometimes referred to as oil collecting agent, are chemicals applied to the water surrounding an oil spill in order to thicken the spill, without the need for mechanical containment, to a point that it can sustain a burn (Buist et al., 2008; Minerals Management Service, 2008). Chemical herders constitute an oil-spill countermeasure that can be used in conjunction with in-situ burning (Sørstrøm et al., 2010).

Chemical herders have been available for several decades (Buist et al., 2008b), but not used extensively offshore to date because they are only effective under largely calm conditions (S.L. Ross Environmental Research, Ltd., 2010). Reviews on the state-of-the-art of oil-spill countermeasures, such as that by D.F. Dickins Associates Ltd. (2004), identified chemical herder behaviour in ice environments as a knowledge gap and subsequent research activities (Interagency Coordinating Committee on Oil Pollution Research, 2009; Minerals Management Service, 2008; and Buist et al., 2008a) focused on the potential utility of herders in responding to oil spills in cold waters, and particularly in ice-covered waters.

Two full-scale burn experiments involving the use of chemical herders were conducted in the offshore of Svalbard, Norway (Minerals Management Service, 2008; Pew Environment Group, 2010). One large-scale experiment with chemical herders was carried out on a free-floating crude oil slick in low (1/10) ice coverage as part of the JIP Oil-in-Ice effort in 2008 (Sørstrøm et al., 2010).

One of the formulations used in recent studies of chemical herders in cold-water conditions is the U.S. Navy cold-water herder formulation (Buist et al., 2008; Buist, 2010). This herding agent was successful in producing slicks in excess of 3 mm and in significantly contracting oil slicks in the presence of ice (Buist, 2010). New formulations of chemical herders are under development and testing (Buist et al., 2010).

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5. Scenarios for oil spill response in ice-covered waters

5.1 Introduction

The purpose of this chapter is to use the information presented in previous chapters to assess the probable capabilities of oil spill response technologies that would be used in the event of a variety of oil spills that could occur in ice-covered waters.

Off shore oil exploration and production within the Arctic and other areas of the world that experience seasonal ice cover is not new. About one hundred oil wells were drilled at locations within the Arctic such as the Canadian Beaufort Sea and in the US waters in the Chuckchi Sea during the 1970s and 1980s. Oil has been produced in Cook Inlet for 50 years. Oil production from the Alaskan North Slope is mainly from wells on land, but is also from several offshore islands. Oil and gas are currently being produced from offshore fields near Sakhalin Island and the Pechora and Kara Seas in Russia.

Oil spill response presents logistical and operational challenges at any location in the world. Oil is being increasingly produced in locations that are remote from substantial infrastructure and increasingly in deep-water locations far from the shore. There are additional challenges presented to effective oil spill response by oil exploration and production in the Arctic and other areas where ice may be present on the sea by the extreme environment; the remoteness, the total darkness and intense cold in winter and changing nature of the sea ice. These factors will make oil spill response more difficult to conduct.

5.1.1 Basis for comparison

Any considerations of the consequences of responding to a hypothetical oil spill will rapidly conclude that the best solution is for the oil spill not to have occurred in the first place; oil spills have the potential to cause damage to ecological and human-use resources. The prevention of oil spills should always have top priority. In this chapter, the starting point for consideration will be that the oil spill described in the scenario has occurred, however regrettable this may be.

Oil spill response methods can only mitigate or reduce the amount of damage that will be caused by an oil spill and cannot reverse any damage caused. The aim of any oil spill response is to limit the damage that could be caused by the spilled oil by limiting contact between the oil and the ecological 'resources' (individual organisms, populations, species, habitats etc.) that would be negatively affected by such contact. The effectiveness of a particular oil spill response technique is best assessed by comparing:

i. The outcome that would occur if no response were undertaken, with

ii. The outcome that would occur if the particular response technique were used.

This comparison process has been formalised as Net Environmental Benefit Analysis (NEBA). A NEBA is an approach to compare and rank the net environmental benefit associated with different management options. For example an oil spill response NEBA should consider the advantages and disadvantages of different spill response options, including a no response, to provide a solution that results in the lowest environmental and socioeconomic impact. NEBA takes into account the ecological and human-use resources that could be affected by spilled oil, the probable consequences in terms of physical and toxic effects that could be caused by the spilled oil and the toxic components within the oil and the probable feasibility of conducting the response techniques under the prevailing conditions. On the basis of this comparison, the probable effectiveness of the oil spill response technique can be estimated by considering the damage that would have been caused if no response had been undertaken and how this would be reduced by application of the oil spill response technique. NEBA is best conducted using location- and season-specific information regarding the ecological and human-use resources that might be at risk.

As has been previously described in this report, the presence of ice and the other environmental conditions that prevail in the Arctic (and other areas with seasonal ice on the sea) will alter the behaviour of the spilled oil and can limit the feasibility, or effectiveness of, the various oil spill response techniques that are available. In order to assess the probability of success of using any of the available oil spill response techniques at an oil spill that could occur in ice-covered waters, the likely outcome first need to be compared to that of an identical oil spill occurring in temperate, ice-free waters.

As has been previously described, spilled oil can behave differently in ice-covered waters than in ice-free, temperate waters. This provides a comparison of the 'base case', no response option for subsequent NEBA.

In the absence of site-specific and season-specific information (see Section 5.1.4) it is not possible to conduct a NEBA to estimate the degree of damage that would be caused to ecological or human-use resources by a particular oil spill scenario. The ecological resources present at any location or time greatly affect the consequences and overall outcome of an oil spill. A relatively small oil spill can cause a great deal of damage if spilled close to a particularly sensitive resource at a critical time, while a much larger oil spill will cause less overall damage if far from oil-sensitive resources at another time of the year.

As stated above, the effectiveness of any oil spill response technique can be estimated by comparing the outcome with no response and the outcome with response, in accordance with NEBA. What can be compared with the available information is the feasibility of conducting oil spill response techniques in ice-covered waters. The limitations imposed on the response techniques by the prevailing conditions have been described in Chapter 5, both for temperate conditions (section 5.2) and by the presence of ice and the other environmental factors that will be present in the geographical areas under consideration (section 5.4).

The comparison to be made is therefore two-fold:

i. Comparing the likely consequences of an oil spill scenario occurring in ice-free, temperate conditions with the likely consequences of an identical spill occurring in the specified circumstances of ice-covered waters with no response, and;

ii. Comparing the likely consequences of using the available oil spill response techniques in ice-free, temperate conditions with the feasibility of using the same techniques in the specified circumstances of ice-covered waters.

This comparison takes into account that the presence of ice will alter the outcome of an oil spill with no response.

5.1.2 Spill release scenarios

Spills or releases of oil into the sea can be the result of a variety of different incidents. The oil may be released onto or into the sea in numerous ways, for example;

1. Oil and gas could be released from a sub-sea wellhead if well control is lost and the preventative methods, such as the BOP (Blow Out Preventer) fail.
2. Oil transported through a sub-sea pipeline could be released into the sea if the pipeline is ruptured by an outside influence such an earthquake or ice scour.
3. The crude oil cargo of a grounded oil tanker would be released into the sea very close to the sea surface. Some oil might flow onto the sea from slightly above the sea surface if the tanks have sustained damage and oil might also flow from below the sea surface.
4. If there is a failure to contain produced oil on an offshore platform it might flow across the top-sides of the structure and then flow off of the platform and onto the sea surface from above.

Released oil can therefore reach the sea surface from underneath (scenarios 1 and 2), can be released almost at the sea surface (scenario 3) or from above (scenario 4).

5.1.3 Prevailing ice conditions

If such incidents occurred in ice-covered waters, the initial behaviour of the released oil would be dependent on the ice conditions, if any, at the time of the incident. The location of the incident would determine the ice conditions that would prevail. If the incident were close to the coast the formation of fast ice would influence the eventual outcome, while an incident further from shore would be influenced by the behaviour of drifting pack ice. The ice conditions under fast ice and drift ice could be:

Sub-class	Fast ice	Drifting pack
a.	Open water conditions	Open water conditions
b.	Freeze-up and growth, some drift and deformation in	Freeze-up, growth, drift and deformation
c.	Total ice cover.	Total ice cover, with drift and deformation
d.	Thaw, break-up and melt. Drift and deformation occurs after break-up	Thaw, break-up, drift, deformation and melt

Table 5.1: Possible ice conditions over an annual cycle

The duration of each phase of the ice cycle and the extent to which it occurs would be dependent on the location of the oil release incident and the prevailing environmental conditions. In principle, any of the 4 oil release scenarios could occur at any of the 4 stages of the ice cycle to produce 16 possible scenarios (Table 5.1).

The feasibility and effectiveness of oil spill response measures would be also be influenced by the ice conditions at the time of the incident. In all but the least severe oil release incidents, it is likely that evolving ice conditions would also need to be taken into account. Consequently the response may have to take place in two or more ice conditions i.e. a late season spill may have to content with processes involved in the melt of ice as well as the freeze-up of ice if it is a prolonged operation. In some combinations of oil release and ice condition scenarios it might be impossible to conduct sufficient oil spill response within a specified time-window.

It is not possible within the scope of this report to consider all the possibilities that could occur in every scenario. The presented scenarios are themselves examples of what could happen and are not intended to be a comprehensive assessment. Nevertheless, they demonstrate some of the considerations that would need to be made when conducting oil spill response operations. Four scenarios, from table 5.1, 1a, 1c, 3b and 4b have been considered further.

Oil release scenario		**Season / Ice condition**							
Event	**Sub class**	**Open water**	**Ice freeze-up and advance**	**Total ice cover**	**Ice break-up and melt**	**Open water**	**Ice freeze-up and advance**	**Total ice cover**	**Ice break-up and melt**
1. Sub-sea blowout scenario	**1a**	●	—	—	—	→			
	1b		●	—	—	—	→		
	1c			●	—	—	—	→	
	1d				●	—	—	—	→
2. Sub-sea pipeline scenario	2a	●	—	—	—	→			
	2b		●	—	—	—	→		
	2c			●	—	—	—	→	
	2d				●	—	—	—	→
3. Sea surface release	3a	●	—	—	—	→			
	3b		●	—	—	—	→		
	3c			●	—	—	—	→	
	3d				●	—	—	—	→
4. Above surface release	4a	●	—	—	—	→			
	4b		●	—	—	—	→		
	4c			●	—	—	—	→	
	4d				●	—	—	—	→

Table 5.1 Scenarios for oil spill response in ice-covered waters

5.1.4 Ecological context of oil spill response

The point of undertaking any oil spill response is that it should reduce the amount of damage done to the environment, ecological resources and to human-use activities (fishing, hunting, tourism etc.) that could be caused by spilled oil.

The effects of oil spills and natural recovery

Spilled oil can cause damage in various ways; to the ecosystem and ecological resources when the oil, or its components, comes into contact with these resources and/or to human activities, such as by contaminating fisheries. The ecological effects of an oil spill can be visibly obvious and distressing; almost immediate effects such as the death of seabirds by hypothermia or drowning resulting from the oiling of their plumage are indeed upsetting. The effects of spilled oil may also be less visible and more insidious by the introduction of potentially toxic oil components such as PAHs (Polycyclic Aromatic Hydrocarbons) into the food web at elevated concentrations that may cause harm to exposed organisms. Nevertheless, the damage done by an oil spill is usually not permanent. Natural recovery, with affected populations recovering from the damage caused by spilled oil will generally occur. The natural recovery process can be slow and take a long time for large, long-lived species and it can take up to 20 or more years for a sensitive habitat to recover after being oiled. For smaller, relatively short-lived species in the marine habitat natural recovery may be complete in one or two years, provided that the inhabitants are not continually exposed to oil trapped within their habitat. The biological consequences of oil spills in Arctic waters need to be studied in greater detail.

Effects of oil slicks; physical oiling and toxic effects

A slick of spilled oil floating on open water would present a relatively reduced hazard while it was drifting in deeper water. Individual seabirds that landed in the oil or dive through the oil in search of prey would become heavily oiled and will probably die of hypothermia. This is particularly the case in colder climates.

Most ecological/economic damage done by oil spills occur when the spilled oil drifts into sensitive coastal habitats or to an area where a very high concentration of the seabirds are feeding. Within a covering of sea ice there are regions of open-water that are surrounded by ice, known as leads or polynyas. These areas provide openings for birds to feed and marine mammals to breath, and thus oil gathering in these regions will naturally have a higher ecological impact.

Spilled oil floating on the sea surface in open water can cause slight effects to the populations of marine organisms inhabiting the upper water column by the release of potentially toxic and slightly water-soluble oil compounds such as the BTEX (Benzene, Toluene, Ethylbenzene and Xylenes), but these also readily evaporate into the air. This evaporation route is not available to oil located under or encapsulated within the ice.

Some toxic effects might be caused to plankton by the substituted naphthalenes that would also be slowly released from the floating oil, but these effects have been found to be short-lived; any plankton killed by exposure to high concentrations of toxic oil compounds will begin to be replaced by re-population from outside the affected area once the original area becomes oil free.

The flesh of fish that swim through an oil slick can become 'tainted' with partially water-soluble oil compounds making them unsuitable for human consumption, but these compounds are often depurated back into the water as the fish swims through the uncontaminated areas of the sea. However the incidences of lesions on fish exposed to oil from natural seeps or from oil spill incidents increases due to the effects of exposure to elevated concentrations of the PAHs (Polycyclic Aromatic Hydrocarbons). PAHs are insoluble in water and remain within the oil, and all crude oils contain in small quantities of PAHs. Ingestion of dispersed oil droplets (which are of a very similar size to plankton) can also be a source of exposure. PAHs can be metabolised into carcinogenic metabolites by organisms such as man and fish that have livers. Longer-term effects can be caused if the spilled oil drifts into shallow water and oil droplets becomes entrained with the sediment in the surf zone and are then deposited onto the coastal seabed. Bivalves, lacking livers to metabolise PAHs, 'bio-concentrate' the PAHs up to high concentrations in some of their organs. The PAH concentration in bivalves levels can reach levels that can be harmful to predators that subsequently consume the bivalves.

Effects of oil slicks in the Arctic

It is beyond the scope of this report to provide comprehensive descriptions of the many and varied coastal and marine habitats present in the Arctic and other areas of the world with "ice-covered waters". There have been several comprehensive studies on various aspects of the effects of oil in Arctic areas, for example the BIOS (Baffin Island Oil Spill) experiments in 1981 (Sergy and Blackall, 1987), and the studies conducted over the following 20 years (Prince et al. 2002).

The general principle that spilled oil will do most damage when it reaches a coastal or shoreline area will be modified by the presence of ice; the 'shoreline' moves with the ice, but holds good on the basis of the studies conducted so far. Spilled oil at sea will do reduced damage while drifting in open water at sea and will do most damage if it drifts into shallow water or reaches the coast. However oil within leads or polynyas may also have a higher ecological impact.

A feature of the Arctic is the very marked seasonal variations. There is a brief 'explosion' of biological activity in the short summer and this supports large populations of migratory birds and mammals. These ecological resources will clearly be at risk from the negative effects of an oil spill when they are present, but one could suggest that they cannot be affected in other seasons when they are not present. However the Arctic food chain is complex and poorly understood and therefore oil impacting one area of the food chain in one season may influence another areas in other seasons.

5.2 Scenarios

As mentioned previously it is not possible within the scope of this report to consider all the possibilities that could occur in every scenario. Therefore we have presented four scenarios, from table 5.1. These are

- Scenario 1a: Sub-sea blowout, end of open water period
- Scenario 1c: Sub-sea blowout, total ice cover
- Scenario 3b: Oil tanker grounding, freeze-up period
- Scenario 4c: Release of oil from above the sea surface

5.2 Scenario 1a: sub-sea blowout, end of open water period

Many of the oil wells that have previously been drilled in shallow water in the Arctic were drilled from gravel islands and the sub-sea blowout scenario considered here would not occur; any loss of well control would result in crude oil flowing from the island and into the surrounding sea.

The start point is an assumed blowout in which, as in the “Deepwater Horizon” blowout, oil and gas come out together. The assumptions of the Canadian Beaufort Sea Project, the first major study on oil in ice (Lewis, 1976), is that the gas-oil mix is 23 cu m of gas per barrel of oil. A buoyant plume of gas bubbles builds up to a diameter of about 80-100 m and carries oil droplets upwards as coatings to the bubbles. Once at the ocean surface (no ice) the oil would begin to form a slick.

The oil flow from a sub-sea blowout would need to be stopped by installing a pre-engineered capping system to bring the well under control. This would take some time, perhaps 2 or 3 weeks, or more and could be very difficult from the logistical and technical points of view. If the capping system were successfully deployed the oil flow from the well would cease, but a large quantity of oil would remain on the sea surface.

If the capping system could not be successfully deployed within the period of open water the oil release would then continue through freeze-up and possibly into the period of continuous ice cover. This situation is considered in Scenario 1c.

The time taken to shut off the oil flow, along with the oil flow rate, would broadly determine the scale (the amount of oil on the sea surface, ice underside requiring response), the potential ecological effects and final outcome of this oil release scenario. As oil exploration moves further into ice-covered waters in remote areas, it is likely that the capability to control a well even after the failure of a BOP will be a mandatory requirement. If this requirement is in place a period of days or weeks of uncontrolled spill is most likely.

<u>a) Environmental conditions:</u>

The cycle of ice conditions that would prevail would depend on the location of the oil well; a drill site near the coast and in shallow would experience fast ice conditions, while a drill site further from the coast and in deeper water would experience drifting pack ice conditions.

During the open-water period the conditions would resemble those at an oil spill in ice-free, temperate waters, albeit with a generally lower sea temperature and sea state. With the onset of freeze-up the oil on the sea surface would find itself floating with increasing amounts of frazil and pancake ice. As freeze-up continued there would be progressively increasing ice coverage, along with the encapsulation of oil within the growing ice cover.

b) Oil detection and monitoring :

Whilst open water areas remain, any oil that surfaces can be detected by active microwave (SAR) satellite sensors provided wind speeds are within the range that those detection methods work. However, as air and water temperatures decrease the oil spill is liable to be lost within visually similar, from imaging of the radar backscatter, grease (frazil) ice covered areas. Thermal infrared imaging, either from satellite if cloud cover permits, or ships or low-flying aircraft, in combination with the radar is then the best possible means of detection. Grease ice areas will be visually similar in the radar, but exhibit increasingly colder temperatures as the ice grows and its freeboard increases.

As ice thicknesses increase, oil on the ice surface is then more likely to be detected visually as ‘oily’ ice is pushed up between floes.

c) Oil fate, behaviour and weathering

The behaviour of the crude oil being released from the sub-sea wellhead and floating up through the water column is considered in scenario 1c. Only the behaviour of oil that has reached the sea surface is considered in this section.

The crude oil that would reach the sea surface would be depleted of some of the partially water-soluble, potentially volatile (and potentially toxic) oil compounds as they would have dissolved into the water column during the transit from the wellhead to the sea surface. As the oil spill will be in relatively cold water the subsequent weathering processes would progress more slowly than to an oil spill occurring in warmer water. The oil would emulsify less and spread to a lesser extent due to the relatively low water temperature. The resultant slick would therefore be somewhat thicker, but smaller in extent than an identical spill in warmer waters.

Oil still at the surface when ice formation occurs would begin to be incorporated into the growing ice cover. If the newly formed, oil-contaminated, ice is free to drift with the prevailing winds it could be many 100s of kilometers away from the original spill site by the time the oil migrates to the surface during the following spring/summer. In this instance the clean up would be logistically difficult to achieve.

d) Response strategy:

If a blow-out occurred in the summer every effort would need to be made to stop the flow of oil, ideally before it reaches the surface in any great quantities, and certainly before winter conditions set in. The primary priority would be to stop the sub-sea oil release. The secondary priority would be to prevent the spilled oil on the sea surface from drifting to especially oil-sensitive ecological and human-use resources.

Depending on the month and location the environmental conditions could be beneficial or detrimental for oil spill detection, containment, and recovery, compared to a similar oil spill in more temperate climates. Examples of beneficial environmental conditions would include:

- 24hr daylight during which response could be conducted, provided sufficient equipment and personnel could be mobilised to the site of the oil release.
- Relatively calm, but cold, sea conditions.

Examples of unhelpful environmental conditions would include:

- Sea ice formation.
- Cold air temperatures with some wind and wave activity leading the icing of machinery.

The response techniques that would be feasible on oil on the ice-free sea surface would be similar to those used at a large oil release in temperate climates; mechanical containment and recovery (booms and skimmers), dispersant use and controlled burning.

Booms and skimmers could be used to contain and recover the oil. However, these operations would become less efficient once even a small amount of ice was present.

Dispersant spraying from aircraft and vessels would be feasible while ice coverage was limited and provided that dispersants could be applied before the spilled oil weathered to a condition when it was not amenable to dispersant use (the time “window of opportunity” for dispersant use).

In-situ burning using fire-proof booms to contain and thicken the oil layers would also be feasible while open water conditions persisted, but would also have to be taken rapidly after the oil was spilled and before the loss of the volatile and flammable oil components prevented ignition (the time “window of opportunity” for controlled burning).

The substantial difference would be that the period of time for which these techniques would be feasible would be limited by the impending onset of freeze-up. If the incident occurred towards the end of the ice-free period the time available to respond by these methods would be brief.

The currently available oil spill techniques would be feasible during the open water period. The feasibility of using booms and skimmers would be seriously curtailed as soon as ice was present to any significant degree. Similarly, the use of controlled or in-situ burning with prior containment with fire-proof booms would be severely limited by the presence of ice. Dispersant use by aerial spraying would be feasible up until about 30% ice coverage and after that could be undertaken by suitably equipped surface vessels. As the ice coverage increased towards 60% or 70% all response techniques would become progressively less feasible.

Open ocean oil fate and trajectory models should do a reasonable job predicting oil spill dynamics and weathering; assuming adequate input parameters are available i.e. meteorological, oceanographic and the oil’s physical and chemical properties.

5.3 Scenario 1c: Sub-sea blowout, total ice cover

Scenario 1c is a sub-sea blowout occurring during the period of total ice cover, perhaps February in the Northern hemisphere.

Once again, it is assumed that well control could be re-established by the use of an emergency system deployed to shut off the oil flow after a period of days or weeks. Since this would have to be inserted through the ice cover serious safety issues need to be addressed as the oil and gas may “pool up” under the ice.

As in Scenario 1a, the released oil and gas would rise towards the sea surface as a buoyant plume of gas bubbles builds up to a diameter of about 80-100 m and carries oil droplets upwards as coatings to the bubbles. This “sprays” the bottom of the ice with finely divided oil droplets over the width of the plume. It is possible that an open water region may form within the region of the rising oil-gas plume.

The oil and gas would spread out along the underside of the ice and collects in the ‘pockets’ of unevenness in the ice coverage. While the sub-sea release was in progress, the affected area would continue to enlarge. See section 2.6 for the spread of oil under ice.

a) Environmental conditions:

February in the Arctic is bitterly cold and the environment can be extremely difficult to operate in. These include: limited daylight, cold temperatures, increased wind chill, reliability of operating machinery. In deep winter there will not be significant amounts of open water, except for sea ice deformation processes such as lead formation. In general the ice cover could be considered as being 100% pack ice.

b) Oil detection and monitoring:

A sub-sea release of oil under total ice cover remains the most difficult to detect with surface remote sensing technologies. Techniques like helicopter mounted ground penetrating radar also may be used to detect oil within an ice cover show promise, but results are often difficult to interpret.

Under fast ice, if the spill is sufficient enough and contains some gas content, then will be rupturing of the ice that will allow oil to the surface and allow detection. Otherwise, if the oil is in smaller quantities, it would be preferable to deploy under-ice equipment such as AUVs and ROV's to map the spill extent using sonar. If the ice is sufficiently thick to allow on-ice field teams, it can act as a platform for AUV operations. Where the ice is too dangerous to allow field teams, then a suitable AUV has to be used.

A full cover of drifting ice is more problematic in that the spill is being transported over a wider area. However, the movement of ice implies that it is broken, and the opening between floes and pushing up of ice into ridges, will aid visual detection from the surface. Again underwater technology is probably the most certain way of mapping the oil spill under ice. As the ice is moving, it will depend on the thickness whether it is suitable for landings by helicopter or aircraft to extend the range of oil spill mapping teams. Otherwise, mapping by AUV would have to be done from a platform or support ship.

A quick way to gauge the potential spread of oil from a drill-site, would be for regular deployment of GPS tracker buoys onto the ice. This can only be done if the release is known to have taken place. The tracker buoys could be supplemented with routine SAR satellite coverage, both to try to determine detection and to monitor ice drift.

c) Oil fate, behaviour and weathering

The oil fate will be slightly different if the blowout occurs under a fast ice cover of drifting pack.

Fast ice: If we are dealing with fast ice (fig. i), i.e. ice which is not moving because of being in shallow water or pinned to the coastline, the gas pressure will break up the ice over the blowout site, and the oil may be largely confined to the resulting hole, especially as the dynamics of the plume will build up a lip of deeper ice around the hole which helps to contain the oil.

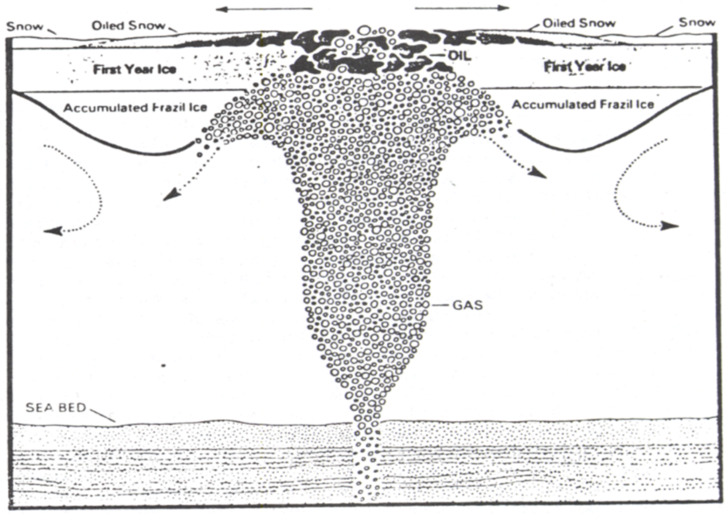

Figure i. A blowout plume hits a fast ice surface developing a hole

In principle the oil, being confined in a small space, can be burned (a risky business if gas is present) or mechanically retrieved. If the oil/gas mixture overflows the lip then the it will flow under the ice, essentially producing a river-like network of oil flow under the ice. Once the flow has been stopped the oil will begin to be encapsulated within the ice cover, if the ice is growing. If growth has ceased for the season the oil will stay as a layer at the bottom of the ice.

Oil will weather very slowly under the ice, and the spill area will be much reduced compared to a similar open-ocean spill (see chapter 2). Once conditions begin to warm however, oil will begin to migrate upwards through the sea ice (see section 2.6.3).

Drifting pack: Drift ice typically moves at 5-10 km/day, giving a downstream drift through a winter of 1500-3000 km. The drift is wind driven and so is not regular in speed or direction, so the trajectory of a given ice floe is likely to include loops and other deviations from the long-term current direction.

The 100 m-wide “paintbrush”, comprising the ice droplets in the rising plume, is now not incident on a stationary surface but on a moving surface where the speed of the ice is such that the oil may not form a continuous layer under the ice. At modest oil flow rates (e.g. the 2,500 barrels/day envisaged by early researchers) the oil is like a wide paintbrush with inadequate paint on it; it paints a discontinuous swath of oil onto the ice underside. At higher flow rates (e.g. the 30,000 barrels/day now stated as possible for the Chukchi Sea) the oil layer is continuous. The oil gathers in depressions and undulations under the ice, or up against the damming effect of pressure ridges, to form a pattern of slicks and pools of thickness up to tens of cm, but with a minimum thickness (set by surface tension) of about 1 cm (figure ii). To track the oil it would be necessary to release GPS buoys at frequent intervals over the blowout site so as to act as tracers for the oiled floes.

Once conditions begin to warm however, oil will begin to migrate upwards through the sea ice (see section 2.6.3). But unlike the oil under the fast ice, under drifting pack it may be far too diffuse to be burned or mechanically removed. Depending on the length of time that has elapsed the contaminated floes may be many 100s or 1000s of kilometres from the blowout site. This is a formidable challenge to clean-up.

As spring turns into summer, the fate of the oil depends on where the floe is. If it is in the central Arctic, the snow on the ice surface will melt to create a network of melt pools on the surface which will now be oiled (see section 2.6.4). This may offer an opportunity for some oil recovery. If the floe is near the ice edge it may melt away completely or break up, depositing the oil in the temporary open water of summer. Again a short window of opportunity for clean-up now occurs, but any skimmer needs to work in the vicinity of other ice floes and so the work would be small-scale and labour-intensive. Also the oil retains its toxicity because the winter encapsulation has prevented the lighter fractions from evaporating or dissolving. In these areas birds, and marine life such as whales, seals, and plankton, would be vulnerable.

d) Response strategy:

If the incident occurred in February an immediate response would be challenging because of the 24hr darkness, the bitter cold and the difficulties of getting substantial logistical support in place at this time of the year. The recovery procedures will be very different depending if the spill occurs under fast ice or drifting pack.

When well control was re-established and the flow stopped there would be a need to establish the extent of the oil and gas trapped beneath the ice. The penetrating ground radar or sensors mounted on underwater vehicles described in Chapter 3 could be one way of doing this. If the blow-out occurred under fast ice the search area would be limited, it would be much more difficult under drifting pack.

Having determined the location and extent of oil on the underside of the ice, and if the ice is suitable for on-ice operations, ice augers could be used to drill a network of holes through which the oil could be pumped out for disposal as waste or burned if suitable temporary storage and transportation was not feasible.

A blowout occurring in the deep winter is very difficult to deal with, due to dangers of the gas release, the environmental conditions at this time of year, and the logistical problems. Even assuming the control of the well is achieved relatively quickly it may be a few months before people can safely work outside to determine where the spilled oil is located and start the recovery operations.

A blowout occurring within drifting pack is even more problematic. If so, satellite tracker GPS buoys will need to be routinely deployed around the site to ensure that the ice can located when conditions are more suited for oil detection and oil recovery operations. Every effort needs to be made to stop the flow of oil quickly, ideally before it reaches the surface in any great quantities. Under ice oil fate and trajectory models have not been verified against in situ spill data and therefore their accuracy cannot be guaranteed.

5.4 Scenario 3b: Oil tanker grounding, freeze-up period

Scenario 3b is a result of an oil tanker grounding during the freeze-up period, perhaps October in the Northern hemisphere, and suffering severe enough damage to release oil from one or more of the cargo tanks. This could occur if ice-strengthened oil tankers were being used to export production from established offshore oilfields or if the tanker was in transit through the Arctic. We assume the accident will most likely occur near the coast.

a) Environmental conditions:

How freeze up progresses is very much dependent on the meteorological conditions at the time. For example calm conditions will produce a smooth ice cover, whilst tempestuous conditions will produce an ice cover that is much more deformed through ice break up and refreeze processes. Moreover, depending on how far into the sea ice life cycle (see Chapter 1) the crude oil released from the tanks of the vessel could find the oil within different ice conditions.

During initial freeze up the spilled oil could flow into a mixture of open-water, frazil and pancake ice. Later in the freeze up process an extended ice sheet will be present. This ice sheet maybe in the form of fast ice if situated near the coast, or if further a field a drifting pack.

b) Oil detection and monitoring :

An accidental release of oil from a ship would release a limited quantity of oil, either in one initial event which was then stopped, either through intervention or by the oil running out, or as a series of partial releases.

In the event of one initial release event, the oil spill detection problem would be similar to that described above for Scenario 1.

In the case of the vessel sinking, probably the only way in which intervention to stop the release of oil is prevented from occurring, it is likely that any oil releases will be in a number of separate smaller events. There will be no warning as to the timing of the these events and so they will only detected by oil finding its way to the surface. This scenario is similar to that of the *Runner-4* incident in the Baltic. Depending on how fast the freeze-up occurs, these release events may be detected as per Scenario 1 above. In the event of a total ice cover forming above the wreck site, this would form a suitable platform for the periodic release of drifter buoys, as per Scenario 2, to enable ice from the incident site to be tracked with certainty, and routine SAR monitoring of ice drift over the area.

c) Oil fate, behaviour and weathering: Compared to the same incident occurring in open water in a temperate climate, the oil flowing from the ruptured tanks and into or onto the sea will be contained to a degree by the ice present.

Oil at the surface when ice formation occurs will be incorporated into the growing ice cover. As the ice grows the oil under the ice will become encapsulated. Generally oil weathers slower under the ice, but oil that has been in contact with the atmosphere will see some additional (atmospheric based) weathering before it is incorporated into an ice sheet.

Encapsulated oil will resurface through oil migration or surface melt processes in the spring/summer oil where it can be cleaned up. If broken ice is present at a high concentrations during the spill, the oil will spread less and be in thicker layers in between the ice floes. The degree of containment by ice will be dependent on the ice coverage and type; in ice coverage of 30% or less the oil will spread as on the open sea, but with and ice coverage of 60% to 70% the oil will be effectively contained (SL Ross and DFG Dickins, 1987). The area of the spilled oil will be much smaller when the oil is spilled with high concentrations of ice present.

If the spill is close to shore the ice cover will most likely be fast ice. Oil spilling onto or into the ice on the sea will remain close to the vessel. Oil spilled into and onto the sea surface amongst broken, drifting pack ice will remain concentrated in a relatively small area, but will drift with the ice away from the grounded vessel. The presence of a more compact oil slick, as compared to that which would be formed in open water, does present some advantages for subsequent detections and response.

d) Response strategy:

A salvage operation would be needed to recover the damaged tanker. Part of this salvage operation would be to remove the remaining crude oil cargo so that it no longer posed a threat to the resources at risk.

Oil spill response activities would need to be concentrated on the relatively compact area of oil contained within the ice coverage. Once again, the aim would be to prevent the spilled oil from drifting to locations of especially high oil-sensitivity. If the broken ice was amongst some fast ice close to shore, the drift of the spilled oil in ice would be limited and it would remain close to the damaged tanker. This would be an advantage compared to a free-drifting oil slick in open water.

Spilled oil contained with drifting pack ice would initially be retained as a relatively compact slick, although would start drifting away from the damaged tanker. Any oil spill response activities would have to ‘chase; the spilled oil. The degree of feasibility in conducting oil spill response would depend on the ice coverage in which the oil was being contained.

The use of booms and skimmers to contain and recover the spilled oil would be not be feasible due to the ice coverage.

Controlled, or in-situ, burning of the thick layers of oil contained in leads between the ice floes (with no fire-proof boom needed if the ice coverage was sufficiently high) would be a feasible response technique for the period of time that the oil remained in an ignitable condition. This period of time (the time “window of opportunity” for controlled burning) would be much longer in the ice conditions than on ice-free water. The spilled oil would be present at lower temperatures, on calmer seas and in much thicker layers than it would be on open water in a warmer climate. All these factors would lessen the rate of oil weathering and the oil would remain in an ignitable state for much longer

Spraying of dispersants from large aircraft would not be feasible once the ice coverage has increased beyond 30%; too much dispersant would be ‘wasted’ as it would be deposited on the ice and not on the oil. It might be feasible to more effectively target the oil by spraying dispersants from helicopters, but their very small payload would limit the scale of the operations. Suitably equipped surface vessels (ice class) would be able to more effectively target the dispersant onto the oil at appropriate treatment rates using multi-lance spray systems and could add the required agitation by creating intense turbulence in the water using their azimuthal drive systems.

The use of dispersant in this way would be slower than spraying dispersant over large areas of spilled oil on open water, but could still be effective in the relatively smaller areas that would be caused by containment of the oil by the ice.

5.5 Scenario 4c Release of oil from above the sea surface

Scenario 4c is a release of oil from above the water (or ice) in the depths of winter. The oil release could be from an oil production facility on (i) a gravel island in the shallow Arctic or from (ii) a fixed installation in deeper water.

a) Environmental conditions:

Mid-winter in the Arctic is bitterly cold and the environment can be extremely difficult to operate in. The ice conditions will be such that there will not be significant amounts of open water, except for sea ice deformation processes such as lead formation. In general the ice cover could be considered as being complete.

The effect of a spill will be very different under fast ice or drifting pack, but given the shallow nature of the bathymetry surrounding a gravel island it will most likely be encased in fast ice.

The more difficult scenario is the fixed installation in deeper water. Being in deeper water the ice surrounding the rig will be within the dynamic ice pack. Therefore any oil on the snow/ice cover will drift away from the oil production facility.

b) Oil detection and monitoring :

Ice detection would be surface technologies such as ships and aircraft, and potentially by SAR satellite monitoring. The combination of darkness and the movement of ice suggest that GPS tracker buoys, as well as remote sensing, will need to be deployed to monitor the drift of the contaminated floes. Again, it is probably easier to track the ice surrounding the platform at the time of the spill and that is known to be contaminated, than it is to detect the oil by remote sensing.

c) Oil fate, behaviour and weathering:

The fate of oil on the ice-snow surface suggests that it will be open to atmospheric weathering processes, such as evaporation. Once the oil is spilled on the ice/snow surface it will spread outwards filling up all available irregularities and preferentially flowing towards low regions on the snow–ice surface. Once the flow of oil has stopped subsequent snowfalls will cover the oil, reducing the rate of evaporation.

The arrival of warmer temperatures in the spring/summer will melt the snow enabling the oil to be visible on the surface again. Any oil at the surface of the ice will absorb solar radiation and cause accelerated melting on the ice surface. This will result in the oil floating in a melt pool of its own creation.

d) Response strategy:

Spilled oil flowing onto snow on top of a continuous sheet of fast ice around a gravel island would resemble an on-land spill of oil. The flow and spread of the oil would be restricted by the presence of the snow and the oil would not flow into the sea beneath the ice. Oil spill response techniques used at sea, such as mechanical containment with booms and recovery with skimmers would clearly be not feasible.

Snow can absorb a lot of spilled oil and the snow would act as to mechanically contain the spilled oil which could then be recovered with mechanical shovels. Subsequent storage of large quantities of oil-contaminated snow could be problematic, especially if it is likely to melt with the thaw and therefore release the oil it contains. The most feasible oil spill response method would be to burn the spilled oil.

References

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APPENDIX. The Fermo statement.

The conclusions reached by a panel of delegates at the recent oil-in-ice international workshop in Fermo, Italy, called "Oil Spills in Sea Ice – Past, Present and Future" (held at Istitute Geografico Polare "Silvio Zavatti", September 20-23 2011). The statement is a list of what needs to be done before we can be said to be sure about the consequences of an oil blowout. Note that the very first desirable item listed is to prevent the oil from ever reaching the ice in the first place, by having a pre-engineering cap ready for action in case a blowout occurs late in the drilling season. This is better than relying on being able to drill a relief well in time and far better than allowing oil to reach the ice through a winter, which would be a disaster for the Arctic environment.

The "Fermo statement" of research needs: (this has been delivered to the Arctic Council Task Force on oil protection)

1. **How best to stop a blowout.** Given the serious environmental impact of an oil blowout on the vulnerable Arctic, the highest priority must be given to methods which shorten the period during which release takes place. Until recently primary reliance has been placed on bringing in a second drilling rig and drilling a relief well even though it could take 60-90 days before successfully controlling and killing the well. Far more useful, in our view, would be a pre-engineered capping system with the ability to install a replacement blowout preventer. If prebuilt and available for rapid deployment such a system could much more rapidly bring the well under control. This is distinct from a containment system, also proposed by various oil companies, which collects oil from a blowout in a sort of hood, with the oil then needing to be removed from site and disposed of at intervals.

2. **How to model oil spread.** It is assumed that oil from a blowout rises in an oil-gas plume, impinges on the lower surface of an ice cover, is encapsulated by the growth of new ice underneath it, and drifts through the Arctic until released in spring by ascent through brine drainage channels to the ice surface. Every stage in this process needs to be modelled and studied more carefully, with special concern about the spring emergence process in the case of multiyear ice where the nature of the brine drainage channels is not well known. Models that have been developed for this process need to be intercompared, in the same way as the Arctic Sea Ice Model Intercomparison Project, to determine which models have validity and predictive power. The small-scale behaviour of oil being encapsulated in ice of different ages and types needs to be measured and modelled by laboratory experiments.

3. **Tracking oil spills.** We do not know enough about the detection of oil spills from space. This applies both to oil spills from marine accidents – ships which sink in ice – and to oiled ice from blowouts where the oil reaches the ice surface in spring and summer after being encapsulated in the ice and drifting with it during the winter. More work, including field trials, needs to be done with electro-optical sensors, including hyperspectral systems, ground penetrating and synthetic aperture radar (SAR). Technologically advanced satellite,

aircraft, and unmanned airborne, seaborne and undersea systems should be exploited and integrated into an effective observing network.

4. **Problems with *in situ* burning.** Although *in situ* burning has been recommended and tested as a technique for disposal of Arctic oil, we do not fully understand the contribution to pollution by the smoke plumes or by the burn residue, especially its potential toxicity. The knowledge base needs to be assimilated into a rigorous net environmental benefit analysis (NEBA).

5. **The role of dispersants** needs to be studied in far greater detail, especially their potential chronic long-term effects. They have been employed in massive quantities in existing spills e.g. Gulf of Mexico, and are currently favoured as a treatment for an Arctic blowout, yet we need to know far more about their effectiveness and toxicity in the Arctic environment.

6. **The physics of large-scale oil entrapment** by features in the ice cover needs to be determined, so as to show whether simple geometric models of oil spread in rough ice are valid. In particular, the porosity of pressure ridges to oil needs to be determined experimentally.

7. **The biological consequences of oil spills** in Arctic waters need to be studied in greater detail. These can range from effects on large mammals (e.g. contamination of seal breathing holes) to small-scale effects (e.g. role of Arctic ocean bacteria in oil consumption, or the effects of sunken oil spill residues on the benthic community). Another key threat is to migratory birds who typically gather in marginal ice zone areas and leads in summer, which is exactly where and when previously entrapped oil is released into the environment. This is an area where the traditional knowledge of indigenous people can be of immense value in the detection of effects and changes, especially in habitats and species movements.

8. **The rapidity of environmental change** is affecting our oil-ice modelling in ways that we cannot fully encompass. Changes in water temperature, ice thickness and ice roughness affect both the mechanics of oil containment by ice and the physics and chemistry of oil interaction with the water column. We need to monitor key Arctic environmental change parameters systematically even though it can be a difficult or lengthy process to derive the rate of change of extreme parameters, such as the depth of the deepest pressure ridge in a given region or the areal extent of deformed ice.

9. **Data sharing and management.** It has often been the case that similar studies of oil-ice interaction have been carried out by industry and academia, with results not being fully shared. Future research on oil in ice should be carried out within the context of data interaction and sharing, such that full benefit can be gained by science from the efforts on both sides. A comprehensive data management system for oil-in-ice results would ensure maximum advantage from the limited opportunities that are available for controlled oil releases.

10. **A rapid scientific response** is needed when any opportunity arises to study oil-ice interaction in the field, e.g. a marine accident in ice. Any such event should

be studied not just from the immediate viewpoint of clearing up the threatened pollution, but also with the larger aim of understanding the nature of the interactions that are taking place.

11. **Delivery of the oil to the ice underside** is a critical function of time of year and state of the sea or ice surface. Studies to date have focused on delivery to the bottom of an established first-year ice sheet, yet a blowout at the end of summer could begin with the oil interacting with a newly freezing water surface or with a variety of young ice types such as frazil, pancake or nilas. How early-winter oil is incorporated into a subsequently growing ice sheet needs to be studied.
12. **The natural background** should be studied in any spill situation. Natural oil seeps occur in many areas that are vulnerable to oil spills, e.g. along the Beaufort Sea coastline and in Baffin Bay, and have an impact which needs to be distinguished from the residual effects of a cleaned-up spill.

It is undeniable that prevention is always better than cure. Prevention of Arctic oil spills can be improved with better information and monitoring. Risks of a surface or subsurface oil spill from shipping or exploration drilling can be decreased if the operations are better designed for the geologic, marine traffic and environmental conditions that may be encountered in a changing Arctic. This includes designing for a wide range of changing ice conditions, storm events, and increased marine traffic. Better understanding of location specific risks requires high resolution temporal and spatial monitoring data and more research into low frequency extreme events.

The Oil Spills in Sea Ice workshop was not sponsored by either the oil industry or by NGOs. The concerns and recommendations expressed by its participants were based purely on our recognition of a clear scientific need. The Chairman and organizer of the meeting was Dott. Maria Pia Casarini, Director of the Istituto Geografico Polare “Silvio Zavatti” (email zip.fermo@gmail.com) and the organising committee comprised Prof. Peter Wadhams (University of Cambridge, p.wadhams@damtp.cam.ac.uk), David Dickins (DF Dickins Associates LLC, La Jolla, dfdickins@sbcglobal.net), Dr Mark Myers (University of Alaska Fairbanks, mdmyers@alaska.edu) and Dr Lawson Brigham (University of Alaska Fairbanks, lwb48@aol.com). The proceedings will be published by the Institute and refereed papers will appear in a special volume of the journal “Cold Regions Science and Technology” edited by Peter Wadhams.

Peter Wadhams